

sttp

Streaming Telemetry Transport Protocol



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Abstract: This specification defines a [publish-subscribe](#) data transfer protocol that has been optimized for exchanging streaming [time series](#) style data, such as [synchrophasor](#) data that is used in the electric power industry, over [Internet Protocol](#) (IP). The protocol supports transferring both real-time and historical time series data at full or down-sampled resolutions. Protocol benefits are realized at scale when multiplexing very large numbers of time series [data points](#) at high speed, such as, hundreds of times per second per data point.

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Introduction

Use of synchrophasors by U.S. utilities continues to grow following the jump start provided by the Smart Grid Investment Grants (2010-2014). Several utilities now have PMU installation counts of 500 phasor measurement units (PMUs) or more and other utilities anticipate being at this level within the next few years. The dominant method to exchange synchrophasor data remains the IEEE C37.118 ^[1] protocol that was designed for and continues to be the preferred solution for substation-to-control room communications. It achieves its advantages through use of an ordered set (a frame) of information that is associated with a specific measurement time. When IEEE C37.118 is used for PDC-to-PDC communication or for PDC-to-Application communication, large data frames are typically distributed to multiple systems.

To address the challenges presented by these large IEEE C37.118 frame sizes, many utilities have implemented purpose-built networks for synchrophasor data only. Even with these purpose-built networks, large frame sizes result in an increased probability of UDP frame loss, or in the case of TCP, increased communication latency due to the higher than normal resend rates. In addition, IEEE C37.118 has only prescriptive methods for the management of measurement metadata. While this prescriptive method can be well-suited for substation-to-control-center use, it becomes difficult to manage as measurement metadata spans multiple analytic solutions. It is also difficult to describe data when measurements are used by different or shared configuration owners or in a wide-area context.

The Advanced Synchrophasor Protocol (ASP) Project was proposed to DOE in response to FOA-1492. In this proposal, the argument was made for a new protocol that overcomes the limitations of IEEE C37.118 for large-scale synchrophasor data system deployments. The new publish-subscribe protocol to be developed under the ASP Project is called the Streaming Telemetry Transport Protocol (STTP). STTP leverages the successful design elements of the secure Gateway Exchange Protocol (GEP) that was originally developed by the Grid Protection Alliance (GPA) as part of the SIEGate project (DE-OE-536).

On May 1, 2017, a DOE grant (DE-OE-859) was awarded to GPA and the other 25 collaborators on the ASP Project (see [Contributors](#) section) to: (1) write a detailed definition of the STTP protocol (*i.e., this document*); (2) develop software to support it including production-grade implementations of STTP API's for multiple development platforms along with a collection of tools to test and validate STTP; and (3) demonstrate and evaluate its efficacy with multiple vendors and utilities.

Scope of this Document

The purpose of this document is to define STTP and to include, as appendices, descriptions as to how to use it, along with its supporting software tools. This STTP specification is focused on effective "streaming data" delivery of which synchrophasor data is a very important use case.

In the [Protocol Overview](#) section of this specification, high-level features and the business value of STTP are presented. The balance of the sections of the specification provide the details of protocol design.

[Appendix A - Initial Team Requirements](#) provides an overview, use cases and both a set of functional and non-functional requirements needed for successful STTP deployment.

[Appendix B - STTP API Reference](#) provides instructions to enable software developers to integrate and use of STTP within other software systems.

[Appendix C - IEEE C37.118 Mapping](#) provides a detailed look at the process of transforming IEEE C37.118 into STTP as well as creating IEEE C37.118 streams from STTP.

[Appendix D - Other Protocol Evaluations](#) provides insight into other protocols that were considered for suitability when developing the STTP use cases and functional requirements.

[Appendix E - TSSC Algorithm](#) provides specification details for the Time-series Special Compression Algorithm (TSSC) which is used by STTP to archive very high compression ratios for streaming data.

[Appendix F - Templates](#) Provides an explanation of how templates can be used with STTP as well as some initial example templates

While the format and structure of this document, established to facilitate collaboration, is different than that used by standards bodies, it is hoped that the content within this document can meet all the information requirements needed to enable repackaging of this specification into draft standard formats.

[IEEE 37.118](#) has enabled synchrophasors to be utilized across the electric utility landscape. It has been the infrastructure on which so many advancements on grid monitoring, model validation, dynamic control and other uses. The huge expansion in the use of 37.118 has exposed some limitation of its use.

Streaming Telemetry Transport Protocol (STTP) looks to advance the work started by designers and users of 37.118 and other protocols and expand the tools available to use synchrophasor data at production scale.

At the conclusion of the Advanced Synchrophasor Protocol (ASP) project in April 2019, Streaming Telemetry Transport Protocol (STTP) will be a well-tested, thoroughly vetted, production-grade protocol, supported by open source applications as well as commercial software from vendors participating in the project. An open source tool suite for STTP will also be developed as part of the project (see [Appendix B](#)) that will include a test harness that will allow future users to test and validate STTP in their systems and API's.

Business case

The STTP protocol is an ideal protocol to share time series data. It allow for transport of measurements with low latency at device speeds from [ICCP](#) / [SCADA](#) (1 update every 1 to 10 seconds) to Synchrophasor (60 or more updates per second) using less bandwidth than any other current protocol. In addition to the real time data STTP support bidirectional sharing of metadata between the communicating applications.

Specifically STTP offers both short-term cost savings and strategic value in that it is:

Intrinsically Robust

By design, STTP packet sizes are small and are optimized for network MTU size. This reduces network level fragmentation, which results in more efficient performance while using [TCP](#) and less overall data loss with [UDP](#). STTP also puts significantly less stress on network routing equipment as well as facilitates mixing of streaming data traffic and other general network communications. With STTP, purpose built networks are not required to reliably support very large synchrophasor measurement data streams.

Security Centric

STTP has been built using a "security first" design approach. Authentication to establish a connection with other parties requires a certificate. While public certificate providers can be used, it is recommended that symmetric certificates be exchanged out-of-band to avoid the risk and cost of management of public keys. Best-practice encryption is also natively available in STTP, but not required, to manage encryption at the network layer.

Reduces First Cost

A protocol similar to STTP called Gateway Exchange Protocol (GEP) has been measured ^[5] to have less than half the bandwidth requirements of IEEE C37.118 ^[1] when used with TCP and simple methods for lossless compression. With the compression, a single signal or measurement point (i.e., an identifier, timestamp, value and quality code) requires only 2.5 bytes. By comparison, IEEE C37.118 requires 4.5 bytes per measurement on average. The signal-based GEP protocol incorporates Pub/Sub data exchange methods so that unnecessary data points need not be exchanged - thereby further reducing overall bandwidth requirements as compared to IEEE C37.118.

Reduces Operating Cost

STTP will allow for automatic exchange and synchronize measurement level meta-data. This is accomplished using a GUID as the key value to allow the self-initialization and integration of rich meta-data with points from multiple connected synchrophasor networks. By including facilities to map and synchronize meta-data STTP eliminates the need to map measurements to a pre-defined set identifiers and dispenses with the cost and hassles of synchronization of individual utility configuration with a centralized registry. The protocol allows for permissions on data subscriptions to be grouped and filtered using expressions assuring that only the signals that are authorized are shared (i.e. for example, all phasor measurements from a specified substation) while the set of points available is dynamically adjusted as PMUs come and go without the need for point-by-point administrator approval.

An Enabling Technology

While STTP was developed with Synchrophasor data in mind, the protocol has the ability to transform how traditional utility data is shared between systems, and stakeholders in many different parts of the utility space.

STTP provides an alternative to the existing method for utility data exchange that will enable future generations of SCADA/EMS systems to both (1) utilize full-resolution synchrophasor data streams and (2) significantly reduce

the cost of maintaining the configuration of components to exchange other real-time data. An ISO/RTO will typically exchange hundreds of thousands of data points every few seconds with its members and neighbors.

i IEC 60870-6/TASE.2 is the international standard used to exchange "real-time" SCADA data among electric utilities. Analog measurement data is typically exchanged continuously every 2 to 10 seconds with bi-modal data such as breaker status information only being exchanged "on change". IEC 60870-6/TASE.2 came into coordinated use in North America in the mid-1990s.

Promising technologies are being developed for cloud computing and these technologies are moving toward native implementations at individual utilities and ISOs. These cloud computing technologies can also be leveraged to support larger native implementations such as those for an interconnect. The common theme among these technologies is the ability to process significantly more data quickly with improved reliability.

It's possible that a protocol like STTP which allows secure, low-latency, high-volume data exchange among utilities at low cost can be a major factor in driving change toward these new technologies. New higher-speed forms of inter-utility interaction will be possible, and new approaches for providing utility information services will be realizable.


Built Upon A Proven Approach

STTP will enhance the successful design elements of the Gateway Exchange Protocol (GEP) as a foundation and improve upon it. GEP is currently in production use by many industry players including [Dominion Energy](#), [Entergy](#), [MISO](#), [Peak Reliability](#), [Tennessee Valley Authority](#), [Florida Power & Light](#), [Southern Company](#), among others.

Definitions and Nomenclature

The words "must", "must not", "required", "shall", "shall not", "should", "should not", "recommended", "may", and "optional" in this document are to be interpreted as described in RFC 2119 [3].

Definition of Key Terms

 All the terms below are hyperlinked to a key source for the definition or to a reference where more information is available.

Term	Definition
binary coded decimal	A binary encoding scheme for decimal numbers that represents each digit with fixed number of bits.
certificate	A file that contains a public key and identity information, e.g., an organization name, hostnames, IP addresses, etc. The X.509 standard defines a standard format for certificate files that can either be self-signed or signed by a certificate authority. Certificates are used in conjunction with public-key infrastructure to provide identity validation and encryption keys used to secure IP transport protocol communications, such as with the TLS protocol. Also called <i>X.509 Certificate</i> .
command channel	STTP functionality, usually implemented using a reliable communications protocol, that is used to exchange command messages in a publisher/subscriber connection.
data channel	STTP functionality, implemented using either a reliable or lossy communications protocol, that is used to send data messages in a publisher/subscriber connection.
data point	A measurement of identified data along with any associated state, e.g., time of measurement and quality of measured data.
data structure	An organized set of primitive data types where each element has a meaningful name.
frame	A data-structure composed of primitive data types that has been serialized into a discrete binary package.
endianess	The hardware prescribed ordinal direction of the bits used to represent a numerical value in computer memory; usually noted as either <i>big-endian</i> or <i>little-endian</i> .
endpoint	A combination of an IP address (or hostname) and port number that represents a unique identification for establishing communications on an IP network. Endpoints, along with an IP transport protocol, are used by a socket to establish inter-device network communications. Also called <i>network endpoint</i> .
Ethernet	Frame based data transmission technology used in local area networks.
encryption key	A set of numbers that are used by an encryption algorithm to transform data into form that cannot be easily interpreted without knowing the key.
firewall	A security system used on a computer network, existing as software on an operating system or a standalone hardware appliance, used to control the ingress and egress of network communication paths , i.e., access to endpoints, based on a configured set of rules. Security zones between networks are established using firewalls to limit accessible resources between <i>secure</i> internal networks and <i>untrusted</i> external networks, like the Internet.
fragmentation	A process in computer networking that breaks frames into smaller fragments, called packets, that can pass over a network according to an MTU size limit. Fragments are reassembled by the receiver.

	Also called <i>network fragmentation</i>
gateway	A network system used to handle multi-protocol data exchange on the edge of a network boundary. For this specification, an edge system that uses STTP to bidirectionally exchange data with another system that uses STTP.
hostname	A human readable label used in a computer network that maps to an IP address. A hostname can be used instead of an IP address to establish a socket connection for inter-device network communications. Resolution of a hostname to its IP address is handled by a DNS service which is defined as part of a system's IP configuration.
initialization vector	A set of random numbers used to initialize an encryption algorithm to reduce recognizable patterns in encrypted data.
IP address	An unsigned integer, either 32-bits for version 4 addresses or 128-bits for version 6 address, used to uniquely identify all devices connected to a computer network using Internet Protocol. The address combined with a port number creates a unique endpoint that is used by a socket to establish a communications channel on a host system.
IP transport protocol	An established set of governing principals that define the rules and behaviors for the transmission of data between two entities when using Internet Protocol. The most commonly used IP transport protocols are TCP and UDP.
measurement	
packet	A block of data carried by a network whose size is dictated by the MTU. Also called <i>network packet</i> .
phasor	A complex equivalent of a simple cosine wave quantity such that the complex modulus is the cosine wave amplitude and the complex angle (in polar form) is the cosine wave phase angle.
port	A 16-bit unsigned integer that, along with an IP address, represents a unique endpoint for establishing communications on an IP network. A port and associated IP address, i.e., an endpoint, and a IP transport protocol is used by a socket to establish a unique communications channel. Also called <i>network port</i> .
primitive type	A specific type of data provided by a programming language referenced by a keyword that represents the most basic unit of data storage - examples can include integer, float and boolean values. Also called <i>primitive data type</i> .
publish/subscribe	A messaging pattern where senders of messages, called publishers, do not program the messages to be sent directly to specific receivers, called subscribers, but instead characterize published messages into classes without knowledge of which subscribers, if any, there may be.
publisher	STTP functionality that is used by a data provider to provision data to be sent to consumers, i.e., subscribers.
null	A value reserved for indicating that a reference, e.g., a pointer, is not initialized and does not refer to a valid object.
serialization	Process of transforming data structures into a format that is suitable for storage or transmission over a network.
signal	
socket	A network communications mechanism, created as a programming language construct, used for sending and/or receiving data at a single destination within an IP network that is established with an endpoint and selected IP transport protocol.

subscriber	Also called <i>network socket</i> . STTP functionality that is used by a data consumer to provision data to be received from providers, i.e., publishers.
synchrophasor	A phasor calculated from data samples using a standard time signal as the reference for the measurement. Synchronized phasors from remote sites have a defined common phase relationship.
switch	A network system, usually existing as a physical hardware, that routes network packets directly to the intended targets. Also called <i>network switch</i> .
time series	A series of data points indexed in time order, most commonly measured as a sequence taken at successive equally spaced points in time.





Acronyms

Term	Definition
AES	Advanced Encryption Standard
API	Application Program Interface
BES	Bulk Electric System
CA	Certificate Authority
DOE	United States Department of Energy
DDS	Data Distribution Service
DNS	Domain Name System
DTLS	Datagram Transport Layer Security
GEP	Gateway Exchange Protocol
GPA	Grid Protection Alliance, Inc.
GPS	Global Positioning System
GUID	Globally Unique Identifier
ICCP	Inter-Control Center Communications Protocol
IP	Internet Protocol
IRIG	Inter-range Instrumentation Group Time Codes
ISO	Independent System Operator
MTU	Maximum Transmission Unit
NaN	Not a Number
NAT	Network Address Translation
PDC	Phasor Data Concentrator
PMU	Phasor Measurement Unit
PKI	Public Key Infrastructure
STTP	Streaming Telemetry Transport Protocol
TCP	Transmission Control Protocol - <i>also as</i> TCP/IP

TLS	Transport Layer Security
UDP	User Datagram Protocol - also as UDP/IP
UTC	Coordinated Universal Time
X.509	PKI Standard for Certificates
ZeroMQ	Brokerless Messaging Queuing and Distribution Library

Document Conventions

Markdown notes in combination with the [Github Emogi](#) images are used as callouts. The standard callouts are:

-  This is a call out in the spec to provide background, instruction or additional information
-  This note use used to highlight important or critical information.
-  This note is used to call out information related to reference implementations or API development.
-  A informal note to document authors to facilitate specification development

Code blocks are shown as:

```
void DisplayHelloWorld() {
    printf("Hello World!");
}
```

Code is also shown `inline` as well.

Presentation Language

This specification deals with the serialization and representation of data in external contexts. To help describe the format of the data a high-level programming syntax will be used. These formats are intended to represent data as it would be structured for transmission, i.e., on the wire format, and not necessarily that of how the data would be stored in memory. The syntax used resembles the "C" programming language, however its purpose is to be illustrative and not language accurate.

Comments

Code comments in this specification begin with `//` and continue to the end of the line. Optionally comments can be represented as beginning with `/*` and ending with `*/`.

Array Types

Any types of data that exist in a series are represented with brackets, i.e., `data[]`, and called arrays. Arrays are defined as a pointer to a block of memory representing the series of data types. Since the array is a pointer, it will be assumed to be pointing to nothing when its value is `null`. An array declared with empty brackets indicates an array of variable size. An array that represents a specific number of elements will be declared with an integer count within the brackets, e.g., `data[2]`. An array with zero elements is considered an empty array.

Numeric Types

Representation of all data types is explicitly specified. The most fundamental unit of data is one byte, i.e., 8-bits. The basic numeric data type is an unsigned byte, called a `uint8`, which represents integers between 0 and 255. All larger numeric data types are multi-byte values encoded as a contiguous sequence of bytes. The following

numeric types are predefined:

```
uint8[2] int16; // Represents integers between -32768 and 32767
uint8[3] int24; // Represents integers between -8,388,608 and 8,388,607
uint8[4] int32; // Represents integers between -2,147,483,648 and 2,147,483,647
uint8[8] int64; // Represents integers between -9,223,372,036,854,775,808 and 9,223,372,036,8
uint8[2] uint16; // Represents integers between 0 and 65,535
uint8[3] uint24; // Represents integers between 0 and 16,777,215
uint8[4] uint32; // Represents integers between 0 and 4,294,967,295
uint8[8] uint64; // Represents integers between 0 and 18,446,744,073,709,551,615
uint8[16] guid; // Represents a 128-bit globally unique identifier
```

Enumerated Types

To represent an enumerated set of possible values, a numeric type is defined called an `enum`. Normally an enumerated type only represents its defined values, however, when the enumerated type values represent bit values, or flags, the enumerated type can represent any number of its possible values at once. Every element of an enumerated type must be assigned a value, as a result values can be defined in any order. Importantly, an enumerated type will only occupy space needed for its maximum defined value when serialized. For example, the following enumerated type would only require one byte:

```
enum {
    Red = 0,
    Green = 1,
    Blue = 2
}
Color;
```

Unless otherwise specified, all enumerated types are considered unsigned.

Standard Endianness

When multi-byte data items are encoded as a sequence of contiguous bytes, they are shown from left to right when described horizontally or from top to bottom when described vertically. Unless otherwise specified, byte-ordering for encoded multi-byte values will always be in big-endian order, i.e., common network byte order.

When extracted from a stream of bytes on a system whose native byte-ordering is little-endian, a multi-byte item, e.g., a 32-bit integer value, could be decoded as follows:

```
uint32 value = buffer[0] << 24 | buffer[1] << 16 | buffer[2] << 8 | buffer[3];
```

Common Structures

The following common code structures are predefined for use within other STTP protocol structures.

Version Structure

Represents a versioned entity, e.g., a protocol version, consisting of a byte for the major and minor components of the version:

```
struct {
    uint8 major;
    uint8 minor;
}
Version;
```


- The `major` field defines the major component of the represented version.
- The `minor` field defines the minor component of the represented version.

NamedVersion Structure

Represents a named entity and associated version, e.g., a compression algorithm, consisting of a `Version` and an ASCII encoded string name.

```
struct {
    uint8[20] name;
    Version version;
}
NamedVersion;
```

- The `name` field defines an ASCII encoded string name for this structure. Field name should be padded with spaces to the right and any serializations should not include a null terminator, i.e., a zero value character.
- The `version` field defines a `Version` number for this structure.

 Small fixed string size for `name` field expected to be sufficient for foreseeable use cases, e.g., specification of compression algorithm.

NamedVersions Structure

Represents a collection of `NamedVersion` entities which includes a count of the total elements.

```
struct {
    uint16 count;
    NamedVersion[] items;
}
NamedVersions;
```

- The `count` field defines the total number of elements in the `items` array.
- The `items` field is an array of `NamedVersion` structures.

Common Functions

The following common functions are predefined for use within other STTP functions.

15-bit Encoding Functions

The following functions take an unsigned 16-bit integer and apply a 15-bit encoding scheme that will serialize the provided 16-bit unsigned integer as either 1 or 2 bytes, depending on its value:

```

// Values greater than 32767 will return null
uint8[] Encode15Bits(uint16 value) {
    if (value <= 127)
        return { (uint8)value };
    else if (value <= 32767)
        return { (uint8)((value & 127) + 128), (uint8)(value >> 7) };

    return null;
}

uint16 Decode15Bits(uint8[] data) {
    if (data[0] <= 127)
        return data[0];

    return (uint16)(data[0] - 128) | (uint16)(data[1] << 7);
}

```

Protocol Overview

STTP is an open, data measurement centric, publish/subscribe, transport protocol that can be used to securely exchange time-series style data and synchronize metadata between two applications. The protocol supports sending real-time and historical data at full or down-sampled resolutions. When sending historical data, the replay speed can be controlled dynamically for use in visualizations to enable users to see data faster or slower than recorded in real-time.

The wire protocol defined by STTP implements a publish/subscribe data exchange model using simple commands with a compressed binary serialization of data points. The protocol does not require a predefined or fixed configuration - that is, the data points values arriving in one data packet can be different than those arriving in another. Each packet of measurement data consists of a collection of data points where each point is defined by a compact structure containing an ID, a timestamp (or sequence), a value and any associated state, (e.g., quality flags).

STTP is implemented using two different communication paths. STTP calls the first one *command channel* and the second *data channel*. In IP based communication each of these channels represent a socket. The actual IP transport protocols for these channels varies based on need. The two most common uses are a single TCP/IP transport for both the command and data channel(UDP or TCP) -or- a TCP based command channel with a UDP based data channel. The UDP implementation reduces latency but adds a level of packet loss as the UDP transport does not acknowledge receipt or resend if missed..

The **command channel** is used to reliably negotiate session specific required communication, state and protocol parameters. The command channel is also used to manage authentication with other STTP instances, exchange metadata on available data points, and request specific data points for subscription. The **data channel** is used to send compact, binary encoded packets of data points.

STTP includes strong access control and encryption and is configurable to allow use of private keys in a highly isolated environment. When encryption and strong identity verification is enabled, STTP utilizes standard Transport Layer Security (TLS) with [X.509](#) identity certificates for authentication.

In this overview section of the STTP specification, data communication fundamentals are presented that set the boundary conditions for the protocol implementation. These boundary cases are followed by an introduction to the remaining major components of STTP.

Background

In typical messaging exchange paradigms, a source application hosts a block of structured data, composed in memory, with the intent to transmit the data to one or more receiving applications. The data has *structure* in the sense that it exists as a collection of simpler primitive data types where each of the data elements is given a name to provide useful context and meaning; most programming languages represent data structures using a primary key word, e.g., `class` or `struct`. Before transmission, the data structure must be serialized - this is necessary because the programming language of the source application which hosts the data structure defines the structure in memory using a format that is optimized for use in the application. The process of serializing the data structure causes each of the data elements to be translated into a format that is easily transmitted over a network and is suitable for deserialization by a receiving application.

The applications that are sending and receiving data structures can be running on the same machine or on different physical hardware with disparate operating systems. As a result, the details of the data structure serialization format can be complex and diverse. Such complexities can include issues with proper handling of the endianness of the primitive data types during serialization which may differ from the system that is de-serializing the data, or differences in the interpretation of how character data is encoded ^[6].

The subject of serializing data structures in the field of computer science has become very mature; many solutions exist to manage the complexities of serialization. Today most computer programming languages, or their associated frameworks, include various options for serializing data structures in multiple formats. However, these solutions tend to only work within their target ecosystems and are usually not very interoperable with other frameworks or languages.

When interoperability is important, other technologies exist that focus on data structure serialization that works regardless of hardware, operating system or programming language. Two of these serialization technologies that are in wide use are Google Protocol Buffers [7] and the Facebook developed Apache Thrift [8]. Both of these serialization frameworks create highly compact, cross-platform serializations of data structures with APIs that exist in many commonly used programming languages.

i For the purposes of this specification, serialized data structures will be referred to as a *frames*, regardless of the actual binary format.

For smaller sized, discrete data structures, the existing available serialization technologies are very fast and highly effective. However, as the data structures become larger, the process of serialization and deserialization becomes more costly in terms of both memory allocation and computational processing. Because of this, large frames of data are not recommended for use by these serialization technologies [9] [10]. Additionally, and perhaps more importantly, there are also penalties that occur with large frames at the network transport layer.

i In the electric power industry, the IEEE C37.118 [1] protocol exists as a standard serialization format for the exchange of synchrophasor data. Synchrophasor data is typically measured with an accurate time source, e.g., a GPS clock, and transmitted at high-speed data rates, up to 120 frames per second. Measured data sent by this protocol is still simply a frame of serialized primitive types which includes data elements such as a timestamp, status flags, phasor angle / magnitude pairs, etc. The IEEE C37.118 protocol also prescribes the combination of data frames received from multiple source devices for the same timestamp into one large combined frame in a process known as concentration. The concentration process demands that a waiting period be established to make sure all the expected data frames for a given timestamp arrive. If any frames of data do not arrive before the waiting period expires, the overall combined frame is published anyway. Since the frame format is fixed, empty data elements that have no defined value, e.g., NaN or null, still occupy space for the missing frames.

Large Frame Network Impact

For the [Internet Protocol](#) (IP), all frames of data to be transmitted that exceed the negotiated maximum transmission unit (MTU) size (typically 1,500 bytes for Ethernet networks [11]) are divided into multiple fragments where each fragment is called a network packet, see [Figure 1](#).

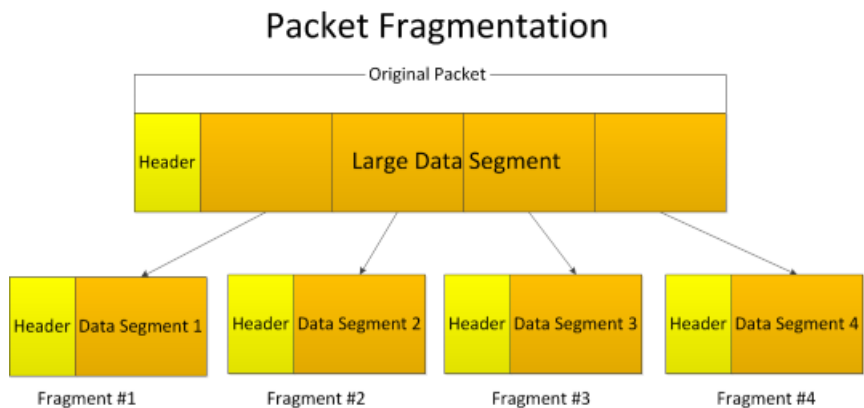


Image Created by Jared Rose, ©2010

Figure 1

Since IP is inherently unreliable, the impact of large frames on an IP network can be determined by the number of network packets required to send the frame.

Network packets can only be transmitted over a connection one packet at a time; when two or more network packets arrive for transmission at the same time on any physical network media, the result is a collision. When a collision occurs, only one packet gets sent and the others get dropped ^[12].

True collisions are generally a thing of the past, as common network infrastructure increasingly use *switch* based technology with physical links that are full-duplex with no shared channels making collisions impossible. However, heavy network traffic can cause very similar issues. As a network is a weakest link problem (can only move data at the rate of the slowest part of the path) When two or more devices are simultaneously transmitting data at high speed to a single device, the switch can find itself in a position where it cannot send all the traffic to the destination port. This is not considered a collision, but the result will be an initial buffering until the small memory on the switch is used up and then it will drop packets.

i Switch technology can also allow for a *pause* frame that is used for flow control at the Ethernet layer. When the connected devices have enabled support for the pause frame, the frame is normally sent when the device is overloaded with data. In this case the data will get buffered by the senders inducing delays, but if send buffers are filled to capacity the result is still the same, dropped packets.

IP supports a variety of different transport protocols for network packet transmission. The most common are [TCP](#), [UDP](#), [UDP-Lite](#), [SCTP](#), [DCCP](#), and [RUDP](#). Each of which behave in different manners when dealing with packet loss. Consequently, many of the impacts a large frame has on an IP network as well as its probability of being delivered without loss is dependent upon the transport protocol used to send the actual frame.

Large Frame Impacts using TCP over IP (TCP/IP)

The most common Internet protocol, TCP/IP, creates an index for each of the network packets being sent for a frame of data and verifies that each are successfully delivered, retransmitting packets as many times as needed in the case of loss. This functionality is the basis for TCP being considered a *reliable* data transmission protocol.

Since each packet of data for the transmitted frame is sequentially ordered, TCP is able to fully reconstruct and deliver the original frame once all the packets have arrived. However, for very large frames of data this causes TCP to suffer from the same kinds of impacts on memory allocation and computational burden as the aforementioned serialization technologies, i.e., Protocol Buffers and network slowdown. The unique distinction for IP based protocols is that at some level, these issues also affect every element of the interconnected network infrastructure between the source and sink of the data being exchanged.

Another critical impact that is unique to TCP is that for data that needs to be delivered in a timely fashion, retransmissions of dropped packets cause cumulative time delays ^[13], especially as large data frames are published at rapid rates. Time delays are also exacerbated during periods of increased network activity which induces congestion and a higher rate of collisions or buffering.

i Synchrophasor data is the source for some real-time visualization and analysis tools which are used to operate the [bulk electric system](#) (BES). This real-time data is required to be accurate, dependable and timely in order to be useful for grid operators ^[14]. Any delays in the delivery of this data could have adverse affects on operational decisions impacting the BES.

Large Frame Impacts on UDP over IP (UDP/IP)

Another common Internet protocol is UDP/IP. Transmission of data over UDP differs from TCP in the fact that UDP does not attempt to retransmit data nor does it make any attempts to maintain the order of the transmitted packets. This functionality is the basis for UDP being considered a *lossy* data transmission protocol, but more

lightweight than TCP.

Even with the unreliable delivery caveats UDP is still limited to packet sizes of the MTU. Any frame larger must be split into multiple smaller packets as described above. UDP attempts to reconstruct and deliver the originally transmitted frame of data. However, if even a single network packet is dropped, the entire original frame is lost and any packets that were already accumulated get discarded ^[15]. In other words, there are no partial frame deliveries - frame reception with UDP is an all or nothing operation.

Since UDP attempts frame reconstruction with the received packets, the impact of large frames of data with UDP are similar to those with TCP and serialization technologies in that there is increased memory allocation and computational processing throughout the network infrastructure.

The more problematic impact with UDP and large frames of data is that the increased number of network packets needed to send a large frame also increases the probability of dropping one of those packets due to a collision. Since the loss of any one packet results in the loss of the entire frame of data, as frame size increases, so does volume of overall data loss.

Impacts of UDP Loss on Synchrophasor Data

For synchrophasor measurement data, UDP is often the protocol of choice. The density of synchrophasor data allows analytical applications to tolerate *some* loss. The amount of loss that can be tolerated depends on the nature of the analytic because as the loss increases, the confidence in the analytic results decreases ^[citation needed]. Another reason UDP is used for synchrophasor data is its lightweight nature; use of UDP reduces overall network bandwidth requirements as compared to TCP ^[16]. Perhaps the most critical reason for use of UDP for synchrophasor data is that UDP does not suffer from issues with induced time delays caused by retransmission of dropped network packets.

For IEEE C37.118 ^[1] deployments, large frame sizes can have adverse affects on data completeness; as more and more devices are concentrated into a single frame of data, the larger frame sizes contribute to higher overall data losses. In tests conducted by PeakRC, measured overall data loss for the transmission of all of its synchrophasor data using IEEE C37.118 averaged over 2% ^[5] when using a data rate of 30 frames per second and more than 3,100 data values per frame. To help mitigate the data losses when using UDP, some companies have resorted to purpose-built, dedicated synchrophasor networks ^[17]. Also companies that have not implemented purpose based networks have used non-critical network infrastructure including the internet to share synchrophasor data due to the fear of over using bandwidth on their respective [Wide Area Networks](#) (WAN).


Although a dedicated network is ideal at reducing data loss (minimizing simultaneous network traffic results in fewer collisions), this is not an option for most companies that treat the network as a shared resource. Also having the option of overbuilding a network or having to upgrade with each increase in Synchrophasor traffic.

Changing the Paradigm with STTP

AS noted above, existing serialization technologies are not designed for messaging exchange use cases that demand sending large or very large frames of data at high speeds. Existing solutions often fall short in terms of timely delivery or data loss depending on the transport protocol used. The obvious solution is to break large data structures into smaller ones, recombining them as needed in receiving applications ^[9]. Although this strategy can work fine for one-off solutions where data structures are manually partitioned into smaller units for transport, this does not lend itself to an abstract, versatile long term solution.

Instead of serializing an entire data structure as a unit, STTP is designed to package each of the distinct elements of the data structure into small groups. Serialization is managed for each data element, typically a primitive type, that gets individually identified along with any associated state, e.g., time and/or quality information, see [Figure 2](#). Ultimately more information is being sent, but it is being packaged differently. By sending the primitive

measurement units directly instead of a full *structure*, many advantages are realized. Primary of the advantages is only data that is changed need be sent.

 For the purposes of this specification a data element, its identification and any associated state, e.g., time and quality, will be referred to as a *data point*.

Mapping Data Structure Elements to Data Points

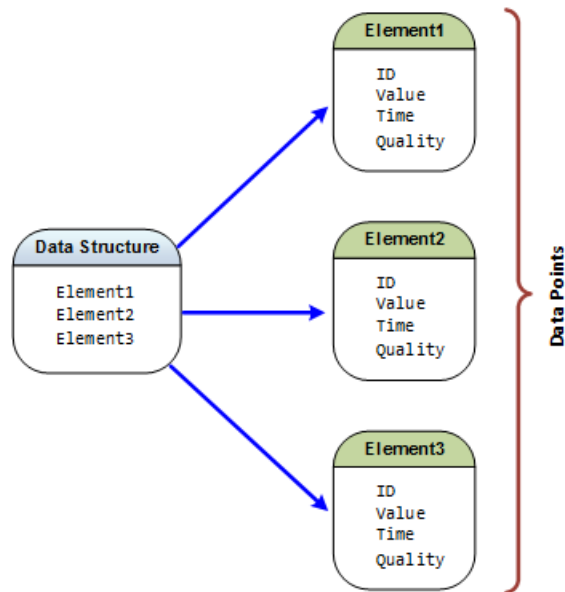


Figure 2

To resolve issues with large frame impacts on IP based networks, a primary tenet of the STTP design strategy is to reduce fragmentation; as a result, STTP intentionally limits the number of data points that are grouped together to form a frame to ensure its size is optimized for transmission over an IP network with minimal fragmentation.

Because each data point is uniquely identified, the elements that appear from one frame to another are not fixed allowing interleaving of data from multiple simultaneous data exchanges - this notion supports the delivery of any number of data structures where each can have a different publication interval, see [Figure 3](#).

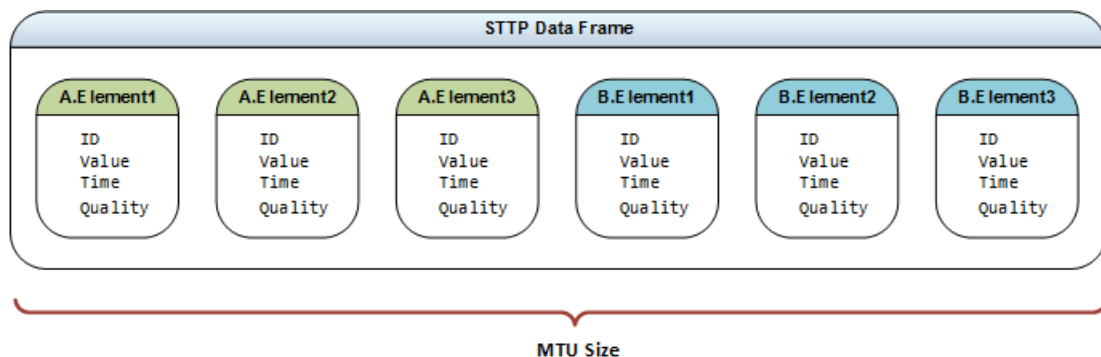


Figure 3

🔧 While it is possible to always target zero fragmentation by making sure the frame size is below the current MTU size, STTP implementations should allow tuning for some fragmentation to accommodate different deployment scenarios and use cases, i.e., allowing target frame sizes that are larger than the current MTU size. For deployments in high-performance network environments, overall loss due to data collisions may be statistically the same for frame sizes that are a few multiples of the MTU.

STTP Bandwidth Impact

Since data points include identity and state along with the primitive type value, serializations of STTP data carry extra information; so by its very nature uncompressed STTP often requires more bandwidth as compared to traditional data structure serialization technologies when each value is updated at a regular time like with data.

Although it will be common for use cases that demand a protocol like STTP, e.g., transmission of large data sets with variable availability at high speeds, to be deployed in environments that are not bandwidth constrained -

simple testing has shown that deviation based compression techniques that have negligible processing impact can yield overall bandwidth requirements for STTP that are equal to or less than other serialization technologies, even when carrying extra information. For synchrophasor data, tests have shown data point serializations to have less than half the bandwidth requirements of IEEE C37.118 ^[1] when used over TCP with simple stateful methods for lossless compression ^[5].

Bandwidth requirements for STTP can often be further lowered by reducing the amount of data being transmitted. For most data structure serialization technologies and protocols, the very process of packaging and sending data in the form of data structures means that some data ends up being transmitted that is not used nor needed by receiving applications. Data reduction for these technologies means creating smaller data structures where it can be costly to maintain separate configuration models for multiple data structures just to achieve bandwidth improvements. Since STTP is designed as a publish / subscribe technology, a receiving application can choose to subscribe to only the individual data points it needs.

Data Point Level Publish / Subscribe

STTP intrinsically manages data at its most fundamental level, primitive types, see [data point value types](#). Each uniquely identified primitive type value represents some form of physical measurement. When measured with periodicity and associated with a timestamp at the moment of measurement, the resulting sequence of measured values and associated timestamps are known as *time series* data. Since data points that are serialized by STTP can include time as part the state information for a value, STTP can be considered a time series data transmission protocol. However, the state information for values being transmitted is flexible - what is *time* for one data point could simply be a *sequence* for another. Additionally, the existence of some data points can be temporal, for example, to exchange a set of binary data, a temporary data point ID may be created that only exists until the binary data transfer is complete.

STTP uses a publish / subscribe based model for control of the data to be exchanged. This exchange is managed at the data point level where data sourced at a sending application, i.e., the *publisher*, makes a set of data points available for publication. A receiving application, i.e., the *subscriber*, will select a subset of the available points for subscription. As new data is made available at the publisher, the subset of the data as selected by the subscriber is transmitted.

One item of note is that with STTP the subscriber may or may not make the connection initiator. A subscriber requests data once the connection is set up. System A can make a STTP connection to System B and at that point System B subscribes to System A. This impacts very few implementation where firewall or other rules limit the direction of any new connection.

Data Point Metadata

A critical part of the publish / subscribe process is defining the data points that are available for subscription. An STTP publisher will define a tabular list of available data point identifiers and associated descriptive information as the *meta-data* that is available to a subscriber.

Each data point includes a unique identifier; regardless of the binary transmission format, this identifier will exist as a statistically unique GUID in the defined metadata for the available data points. This makes the metadata from multiple publishers easier to merge into local repositories used by a subscriber.

At a minimum, each row in the STTP publisher metadata will include the GUID based data point identifier, a short human readable alpha-numeric *tag*, the primitive data type used for the value of the data point, a description, the enabled state and timestamps for the creation, last update and deletion of the data point.

It is expected that vendors and other stakeholders will publish standard grouping of metadata. They may or may not be based on other standards like [Common Information Model](#) CIM. By defining standard sets of metadata it

will allow for automatically syncing meta-data for like applications.

Metadata in STTP is also designed to be extensible. Different industries may require different kinds of available metadata in order to properly map and integrate with other protocols and environments. To accommodate the extensibility, other tabular datasets can be made available by a publisher as needed.

Data Point Access Control

STTP puts publishers in full control of access to data. A publisher may expose all data to every connection or alternatively can choose not to allow connections and/or expose any data to a subscriber that is not strongly identified (authenticated). Publishers can choose to restrict data access at an individual data point level, a group level or at an identified subscriber level.

In order to support group level access, selection of available points for an identified subscriber or a group can be controlled by an expression. Expression based access control means that the even as the data sources available to a publisher change, the expressions will still apply and need not be updated. As an example, metadata will need to contain information about the primitive data type for a given data point - an expression based on this data type may look like the following:

```
ALLOW WHERE DataType= 'BOOL '
```

For this expression, all data points as defined in the metadata that have a data type of `BOOL` would be allowed for the group or identified subscriber. This expression would cause the allowed metadata to dynamically change as the available source data configured in the publisher changed.

Data Transport Channels

Although not precluded from use over other data transports, the design of STTP is targeted and optimized for use over IP, specifically TCP/IP and UDP/IP. Even so, since the command/response implementation and data packet distribution of the STTP protocol is fairly simple, it is expected that commonly available middleware data transport layers, such as [ZeroMQ](#) or [DDS](#), could easily support and transmit data using the STTP protocol should any of the messaging distribution and management benefits of these transport layers be useful to a particular deployment environment. However, these types of deployments are outside the scope of this initial documentation. STTP integrations with middleware layers should be added as reference implementation repositories to the STTP organizational site if they are utilized ^[4].

Establishing Connections

For normal STTP connections that are established using IP sockets, the actual details of establishing a socket connection are specific to the operating system used as well as the specific programming language used. However, major implementations share much in common as to let us talk in generic terms here. The minimum information needed to create a socket is (1) an endpoint, i.e., the IP address and port number, (2) the desired IP transport protocol, e.g., TCP or UDP, and (3) the type connection to be established, i.e., a *server-style* socket or a *client-style* socket. A server-style socket is one that listens for connections from clients. A client-style socket is one that connects to a listening server socket. Client-style sockets are always the *initiators* of any given connection, i.e., client sockets always "make the call" to server sockets to begin communications.

Forward Connections


As noted in the overview, there are times that we want the data sender in STTP to be the initiator of the socket connection for security reasons. Under typical conditions STTP publishers, the data provider will set up a server-style listening sockets, and STTP subscribers, as data consumers, will use client-style sockets to initiate connections to a publisher's listening socket. Establishing a server-style socket for a publisher and client-style sockets for any subscribers describes a connectivity model for STTP that is called a *forward connection*. Forward connections are expected to be the normal use case for STTP publisher/subscriber connections. However, for an STTP connection it does not matter which party, publisher or subscriber, is the initiator of the socket connection.

Reverse Connections

In STTP it is perfectly valid for a publisher to initiate a client-style socket connection to a subscriber that is listening with an established server-style socket. This type of connectivity model is called a *reverse connection*. Since a client-style connection is the only type of socket that can initiate a connection, a reverse connection requires the publisher to be the initiator of a connection such that the target subscriber would be able to receive data.

Reverse connections flip the normal responsibilities of a publish/subscribe messaging pattern by having parties that provision the data also be the initiators of a connection. Data subscribers, which might otherwise come and go as needed, now become a persistent network resource that needs to be readily available for a connection from its publisher. Reverse connections can require more data flow planning and network engineering to ensure that connections are initiated from the proper locations while having the data reliably flow to the desired locations. Most often a *reverse connection* is used to ensure connection is initiated from an environment of higher security to one of a lower security as is cyber security and NERC CIP best practice.

Regardless of how a connection is established, forward or reverse, the functions, roles and responsibilities of the participants will not change, i.e., a publisher shall still be the provider of data and the subscriber shall still be the consumer of data. Additionally, any required protocol negotiations by the parties continues as normal once the connection has been established.

 Increased flexibility in the connectivity models for STTP is necessary so that security boundaries that have been enforced with firewall rules can be maintained. A common use case is that the publisher, and the data it has access to, will exist in a secure network environment and the subscribers, which need access to the data, will exist in less secure network environments. In these scenarios, firewall rules will prohibit any connections to be initiated from an environment that is considered to be less secure. However, such environments normally allow connections to be initiated from inside the secure environment out to listening connections in less secure environments, see [Figure 4](#). Described more simply, nothing can reach in to systems in the secure environment, but systems in the secure environment can reach out - this is much like how a computer in a home network can access the public Internet through a router, but the router's built-in

firewall prevents systems on the Internet from accessing the home computer. Although reverse connections may initially seem counter-intuitive, they exist as a firm STTP requirement to allow for successful data exchange from within secure environments.

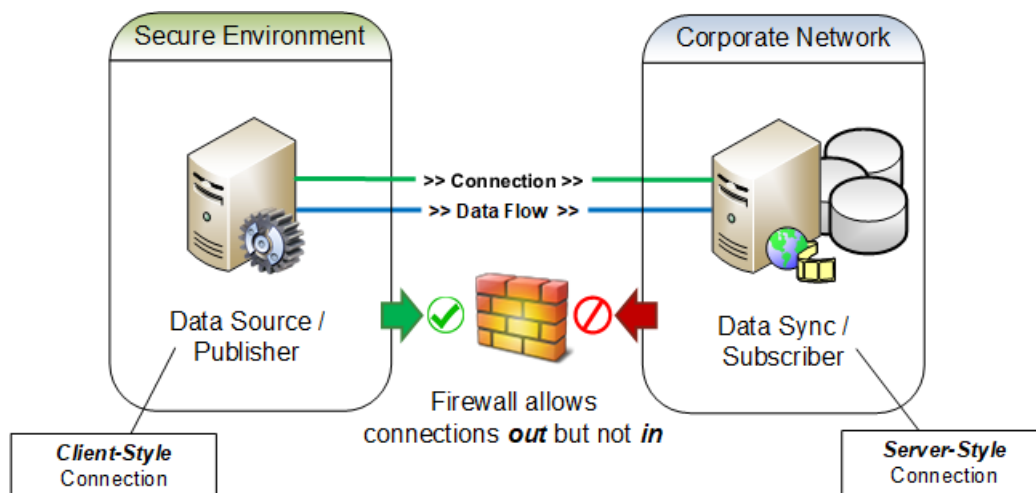


Figure 4

Bidirectional Data Exchange

For simple TCP only based connectivity configurations, once a connection has been established between two systems a communications pathway exists such that data can flow bidirectional. This is true regardless of which party uses a client or server socket or the connectivity model in use, i.e., a forward or reverse connection.

Since data in a TCP based connection can easily move in both directions, both parties can simultaneously enable both publisher and subscriber functions. This allows STTP to be used in a data exchange *gateway* capacity allowing for bidirectional data exchange with simplified connectivity requirements. The only decision two parties would need to make in this mode of operation is which STTP instance acts as a server and which instance acts as a client.

More traditional configuration models can be established for bidirectional data exchange as well, such as, restricting server-style sockets to publisher functions with connecting client-style sockets restricted to subscriber functions. In this configuration, both parties would have listening server-style sockets for publisher functions and both would need to establish client-style sockets for subscriber functions. This may be the preferred mode of operation when one or more parties want to have more control over subscriber connectivity and security, or desire to use UDP for data transmission.

Using UDP for Data Transmission


By reducing the STTP capability set to functions that support lossy data transmission, data channel functionality in STTP can be established over a UDP connection. When using a UDP based data channel, command channel functionality is expected to be established over a TCP connection. A reliable command channel is needed in order to properly manage initial protocol negotiations, which includes establishing the operational modes of the publisher/subscriber connection, and provides the ability for subscribers to choose the data to be received.


STTP data channel functionality is designed to be sent without the expectation of a response in order to accommodate connections that have unidirectional data flows, such as UDP. Any functionality related to transmitted data that requires a response, e.g., a delivery receipt, must be managed by the command channel.

🔧 The initial subscriber command request sent to a publisher should include the UDP port that the subscriber wishes the publisher to use, see [operational modes negotiation](#). The destination UDP port is a local resource for the subscriber host machine and therefore under its control. However, UDP endpoints

often need specific firewall rules to allow data transmission, thus requiring a preselected port to be established during the initial configuration process.


It is expected that STTP will normally be used over Internet Protocol. In order to meet the entire set of capabilities as enumerated in this specification, a TCP/IP based connection shall be required for at least the *command channel*. A single TCP connection can be used to meet the requirements for both the *command channel* and *data channel* functions giving the full capability for both basic and advanced STTP functions. Alternatively a connections could use UDP/IP on a separate socket for *data channel*. Using UDP connections for *data channel* does reduce the set of capabilities that can be supported. As an example, since UDP is a **lossy** transmission protocol, so any capabilities that implement stateful connection such as advanced compression or function that require delivery guarantees cannot be supported using UDP *data channel*.

 UDP only style deliveries, either unicast or multicast, of data using STTP can only be accommodated with substantial capability restrictions. That is, with no reliable command channel, consumers of STTP data provided over a UDP only connection would be subject to publisher established formats, content and resolution of the data being delivered. Alternately, establishment of a UDP based command channel would require adjustments in protocol behavior to accommodate failures to send command requests and/or receive responses due to lack of delivery guarantees. While it is expected that with the right set of initial assumptions and capability restrictions that STTP could effectively operate with a UDP only connection, the main text of this specification will intentionally remain silent on such details for the sake of simplicity, clarity and brevity.

 Add an appendix to discuss how a UDP only STTP transmission should work so that needed caveats and capability restrictions can be established for this behavior. Describing this operation is important given that UDP only data transmissions for synchrophasors is widely used in production environments today. UDP only deployments, e.g., multicast, can also be very useful in lab environments for simplicity in data distribution. Regardless of the veracity and logic for the technical arguments that can be made to not use UDP, either by itself or in combination with TCP, by not defining the protocol behavior in these modes of operation there is increased risk of the protocol not being initially adopted or accepted. Having these behaviors documented will help alleviate any non-standard implementations that may crop up otherwise. Reference implementations will be adjusted to accommodate these use-cases as time allows, however UDP options will be implemented at lower priority. During code development, UDP use cases will be kept in-mind such that future iterations of the reference implementations can accommodate UDP based behaviors and functionality more readily.

Secure Connections

For data transmissions over the Internet or those that need to transmit sensitive data, a secured socket connection should be established for STTP communications. To secure a connection, a socket must be established with standard [Transport Layer Security](#) (TLS) using a signed X.509 certificate. TLS is used to encrypt, authenticate and attest to the integrity of the data being transmitted over STTP.

 As of the writing of this specification, the latest available TLS version is 1.2, with the 1.3 version still in draft. The default stance for STTP implementations is to always default to the latest, hence most secure, version of TLS available. However, since different operating systems and programming languages may not be up-to-date with the latest TLS versions and different implementations of STTP need to be interoperable, the TLS version to use for any publisher/subscriber connection should be configurable. However, STTP implementations should log a warning if a connection is established using a version of TLS that is less than the latest supported version for the implementation.

TLS is a protocol layer that sits above TCP, as a result, secure connections are established in exactly the same manner as basic TCP connections, however once the socket is connected, TLS adds the needed negotiations to

enable security. Just like with a socket, the actual details of establishing a secure TLS session are specific to an operating system and ultimately the programming language being used.


Certificate Validation

The use of [X.509](#) certificates are required in order to secure an STTP connection using TLS. For STTP, certificates are used to verify the identity of a connection, as well as to provide data encryption and integrity guarantees. For confidence in the certificates being used, STTP defines the operations needed to ensure that certificates are valid.

STTP implementations have the capability to use either self-signed certificates or those signed by a [certificate authority](#) (CA). For CA issued certificates, trust is delegated to the CA, which normally means the CA needs to be accessible during the validation process.

For self-signed certificates, trust exists between the two parties exchanging certificates, which means each party needs to agree to keep the certificates private and to notify the other party if the host machine is ever known to be compromised, i.e., where an external party may have been able to gain access to the private keys stored for the certificate. Since trust for self-signed certificates is between the two parties exchanging data, STTP requires that the certificates be exchanged in advance - a self-signed cert sent during TLS negotiations must be considered untrusted. Self-signed certificates should always be exchanged out-of-band, i.e., not over the STTP protocol, and should never include the private keys.

Certificate validation is handled in terms of the type of socket connection that is established, i.e., a client-style socket or a server style-socket. The STTP functional role of the party, i.e., publisher or subscriber, does not affect the certificate validation process because both client and server style connections can be setup to validate certificates. Consequently a publisher can validate subscriber certificates and a subscriber can validate its publisher certificate regardless of which connectivity model in use, forward or reverse.

 Through configuration, STTP implementations should be able to gracefully accommodate use cases where the certificate validation steps encounter errors, e.g., self-signed certificates returning an expected untrusted root error or a common name mismatch error ^[18]. This is important since STTP can be deployed in environments where there is no public Internet access or where a client connection may appear to have a mismatched IP addresses due to a difference caused by NAT configuration. Certificate error conditions such as the inability to verify hostnames, IP addresses or contact an issuing CA should be mitigatable through configuration of the STTP implementation. For user interfaces, appropriate warnings and feedback should be provided as to the possible impact on security when errors are suppressed. Any new configurations should always default to the highest level of security and error warnings but be easily adjustable for any given environment as deemed appropriate by a user.

Client Certificate Validation

For server certificates issued by a CA that need validation, STTP implementations supports traditional client-style connections with TLS similar to how a browser connects to a secure site with HTTPS and validates the site's certificate. In this mode, when an STTP client-style socket connects to a server-style socket that has a CA issued certificate, with the certificate being provided by the server as part of the data in the TLS negotiation process, the client shall validate the server's certificate by (1) verifying the certificate's signature, (2) ensuring the certificate has not been revoked by checking the certificate revocation lists, and (3) checking that the information in the certificate information is valid, i.e., validating that one of the hostnames or IP addresses listed in the certificate subject field match the connection information for the server.


Validation of self-signed server certificates are similar to those for CA signed certificates but does not include steps that engage a CA. In this mode, when an STTP client-style socket connects to a server-style socket that has a self-signed certificate, the client shall validate the server's certificate by (1) verifying the certificate's signature, and (2) checking that the information in the certificate is valid, i.e., validating that one of the hostnames or IP

addresses listed in the certificate subject field match the connection information for the server.

Server Certificate Validation

STTP implementations also support server-style connections with TLS, with the ability to validate client certificates issued by a CA. In this mode, when an STTP server-style socket accepts a connection from a client-style socket that has a CA issued certificate, with the certificate being provided by the client as part of the data in the TLS negotiation process, the server shall validate the client's certificate by (1) verifying the certificate's signature, (2) ensuring the certificate has not been revoked by checking the certificate revocation lists, and (3) checking that the information in the certificate information is valid, i.e., validating that one of the hostnames or IP addresses listed in the certificate subject field match the connection information for the client.

Validation of self-signed client certificates are similar to those for CA signed certificates but does not include steps that engage a CA. In this mode, when an STTP server-style socket accepts a connection from a client-style socket that has a self-signed certificate, the server shall validate the client's certificate by (1) verifying the certificate's signature, and (2) checking that the information in the certificate is valid, i.e., validating that one of the hostnames or IP addresses listed in the certificate subject field match the connection information for the client.

 For CA issued certificate validations, the listed step that requires STTP to "validate that a certificate has not been revoked by checking the certificate revocation lists", is feature that is commonly handled by libraries that implement TLS. This step is iterated here as a requirement in case an STTP implementation uses a TLS library that does not automatically handle this feature.

UDP Security with Secure Connections

When a UDP data channel is in use and needs to be secured, it is expected to be associated with a command channel that is secured using TLS. With communications for the command channel already secured, it is safe to exchange encryption keys that can be used to secure the UDP traffic.

STTP secures UDP traffic using the AES encryption algorithm and a 256-bit publisher generated symmetric encryption key and initialization vector that shall be provided to the subscriber over the TLS secured command channel, see [secure data channel command](#).

 Although TLS is normally used with reliable IP transport protocols such as TCP, TLS has also been implemented for UDP using the Datagram Transport Layer Security (DTLS) protocol. This protocol could allow a UDP channel to be secured without having a preexisting TLS secured command channel and even provide security for UDP only style data deliveries. However, as of the writing of this specification, DTLS implementations were not widely available on the platforms and programming languages that were being targeted for initial STTP reference implementations.

Commands and Responses Overview

As described previously, STTP is implemented using a *command channel* that is used to reliably negotiate session specific required communication, state and protocol parameters. Command channel functionality includes establishing communications with other STTP implementations, exchanging metadata on available data points and the ability to request data points for subscription. Any messages, such as commands, transmitted with the expectation of receiving a response will only be sent over the command channel, as such this functionality requires a reliable transmission protocol, e.g., TCP.

This section describes the available commands and responses that define the functionality of STTP.

Message Formats

Commands and responses are defined as simple binary message structure that also may include a payload. The details for the payload of the message will depend on the specific command or response code.

Message Payloads

Payloads in STTP are defined as a byte arrays prefixed by an unsigned 16-bit integer representing the array length. Implementations of STTP should make target payload sizes configurable, but all payloads delivered by STTP must have a fixed maximum upper length of 2^{16} , i.e., 65,535, less 3 bytes for the packet overhead.

```
uint8[] payload;
```

It is permitted to send an empty payload if the [command code](#) does not require a payload.

Command Structure

Commands are used to manage primary STTP functionality. The following defines the binary format of a `Command`, see [Figure 5](#) for an example:

```
struct {
    uint8 commandCode;
    uint16 length;
    uint8[] payload;
}
Command;
```

- The `commandCode` field defines the command code value for the command message, see defined [command codes](#).
- The `length` field defines the length of the entire packet in bytes.
- The `payload` field is a byte array representing the serialized payload associated with the `commandCode`.

Example Command Structure for a `DataPointPacket`

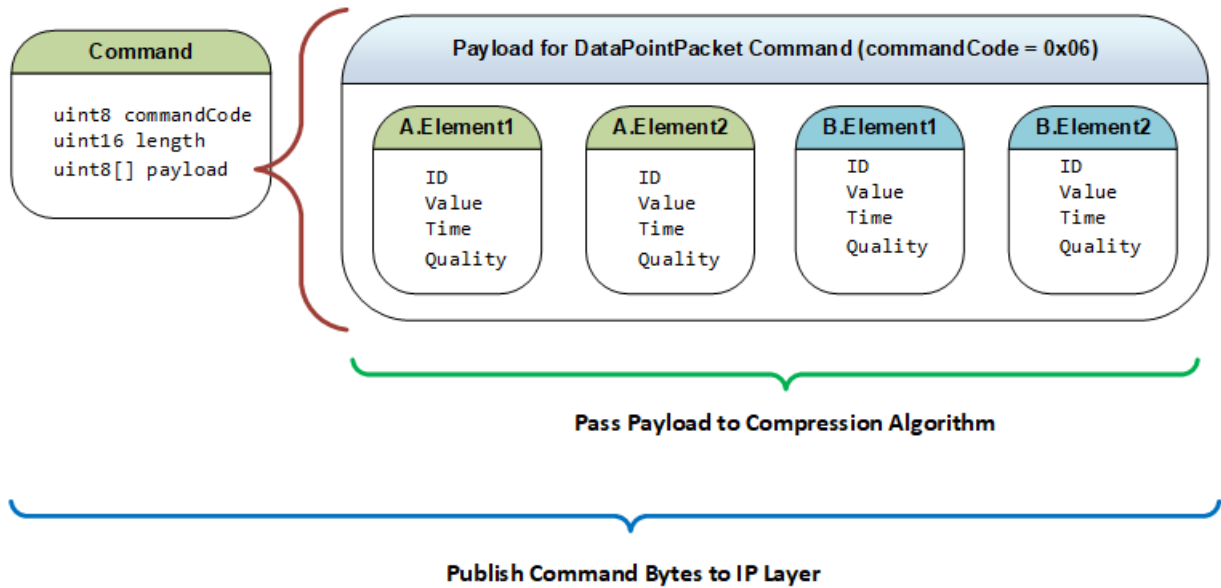


Figure 5

Response Structure

Some form of response exists for every command. Responses take the same format as commands but are distinguished with a different command code. Sometimes, successful responses are implied and not expressly stated. However, in these cases, it's still permitted to send a successful response in addition to the command. Responses for most commands will be either `Succeeded` or `Failed`. The following structure defines the binary format of a `Response`:

```

struct {
    uint8 responseCode;
    uint16 length;
    uint8[] payload;
}
Response;
  
```

- The `responseCode` field defines the response code value for the response message, see defined [response codes](#).
- The `length` field defines the length of the entire packet in bytes.
- The `payload` field is a byte array representing the serialized payload associated with the `responseCode`.

Command Details

The following table defines the commands available to STTP. Commands that expect a response define the command channel functions, those that do not define the data channel functions.

Code	Command	Source	Response	Description
0x01	BeginFragment	Both	No	Indicates a large packet is being sent.
0x02	NextFragment	Both	No	The next fragment of a large packet. Follows <code>BeginFragment</code> .
0x03	GetMetadataSchema	Subscriber	Yes	Requests the database schema and version of the metadata.

0x04	GetMetadata	Subscriber	Yes	Requests specific records of the metadata based on the schema.
0x05	Subscribe	Subscriber	Yes	Adds/Removes a desired set of data points that will be received.
0x06	SendDataPoints	Publisher	No	A packet that contains normally encoded data points.
0x07	SendDataPointsCustom	Publisher	No	A packet that contains specially encoded data points.
0x08	RuntimeIDMapping	Publisher	Yes	Defines runtimeIDs for DataPointIDs.
0x09	NegotiateSession	Publisher	Yes	Establishes session roles and supported features for a connection.
0x0A	BulkTransport	Publisher	No	For sending large buffers, like files.
0xFF	NoOp	Both	Yes	Periodic message to allow validation of connectivity.

Begin Fragment Command

If sending a packet that is larger than the negotiated maximum packet size, it must be fragmented. This command is the first in a series of fragment commands that define the entire fragment.

If the session supports it, fragmented data is commonly compress. It's possible that a compressed data fits into a single fragment, therefore this command will not be followed by subsequent `NextFragment` commands.

Fragmented packets must be sent one at a time in sequence and cannot be interwoven with any other kind of command.

```
struct {
    int32 totalFragmentSize;           //The size of all fragments of the fragmented packet
    int32 totalRawSize;               //The uncompressed size of all of the compressed segments
    int8  commandCode;               //The CommandCode of the data that is fragmented
    int8  compressionMode;           //The compression algorithm that compressed this packet. Can
    //(uint16) lengthOfFirstFragment //This field is not specified and is implied from the packet
    uint8[] firstFragment             //This is the first fragment of the data.
}
BeginFragmentCommand;
```

Next Fragment Command

This packet always follows `BeginFragment` and will be repeated in order until all of the data has been transmitted.

There is not a Finished command, therefore, once the total number of bytes have been transmitted as defined in `BeginFragment` . The command has completed.

```

struct {
    //(int32) offset           //This is implied. It's the total number of bytes that have been r
    //(int32) lengthOfFragment //This field is implied. Packet Length - 3.
    uint8[] fragment         //The next fragment of the sequence.
}
NextFragmentCommand;

```

Get Metadata Schema Command

Requests that the current version of the metadata database be sent, along with the schema. While this information is not required, it's important to know this when checking if one's metadata is out of synchronization or if additional user defined metadata tables exist.

```

struct {
    bool includeSchema //Without this set, the response will only include the database version a
}
GetMetadataSchemaCommand;

```

Get Metadata Command

Requests specific tables of metadata. If supported by the connection, custom queries and filters can be also be specified as part of the metadata request. There is only permitted one table per request.

```

struct {
    guid schemaVersion //If not Guid.Empty, is used to verify that the current schema has
    int64 revision      //If isUpdateQuery=true, the query returns all changes since the s
    bool isUpdateQuery  //specifies if this query should only return the deltas, of the en
    SttpQueryExpression query //The query itself. EX: SELECT * FROM Table where Column = 1234
}
GetMetadataCommand;

```

The results for this command are streamed and can be broken into multiple packets if needed.

Subscribe Command

Updates the subscription for new measurements. This update can be to add, remove, or replace an existing subscription.

This command is broken up into sub commands that can be combined into a single packet. The sub commands include:

- Subcommands
 - `ConfigureOptions` - Defines options for the measurements about to be selected. Such as priority; dead-banding; start/stop times; sample resolution.
 - `AllDataPoints` - Subscribes to everything
 - `DataPointByID` - Specifies individual data points
 - `ByQuery` - Specifies some kind of query to use to select the measurements.

```
enum {
    Replace,
    Remove,
    Append,
}
SubscriptionMode;
```

```
struct {
    SubCommand ConfigureOptions
    SubscriptionMode mode
    SttpNamedSet options //A set of options for the points about to be specified.
}
ConfigureOptions;
```

```
struct {
    SubCommand AllDataPoints
    SubscriptionMode mode
}
AllDataPoints;
```

```
struct {
    SubCommand DataPointByID
    SubscriptionMode mode
    SttpPointID[] points //An array of points.
}
DataPointByID;
```

```
struct {
    SubCommand ByQuery
    SubscriptionMode mode
    SttpQueryExpression query //A query that specifies the points to use. The columns specif
}
ByQuery;
```

Some examples of what can be exchanged in the ConfigureOptions include these items.

Signal mapping structures:


```

enum {
    Level0 = 0, // User level 0 priority, lowest
    Level1 = 1, // User level 1 priority
    Level2 = 2, // User level 2 priority
    Level3 = 3, // User level 3 priority
    Level4 = 4, // User level 4 priority
    Level5 = 5, // User level 5 priority
    Level6 = 6, // User level 6 priority, highest
    Level7 = 7 // Reserved system level priority
}
Priority; // 3-bits

enum {
    Latest = 0, // Data down-sampled to latest received
    Closest = 1, // Data down-sampled to closest timestamp
    BestQuality = 2, // Data down-sampled to item with best quality
    Filter = 3 // Data down-sampled with DataType specific filter, e.g., average
}
ResolutionType; // 2-bits

enum {
    Timestamp = 1 << 0; // When set, State includes Timestamp
    TimeQuality = 1 << 1, // When set, State includes TimeQualityFlags
    DataQuality = 1 << 2, // When set, State includes DataQualityFlags
    Sequence = 1 << 3, // When set, State includes sequence ID as uint32
    Fragment = 1 << 4, // When set, State includes fragment number as uint32
    PriorityMask = 0xE0, // Mask for Priority, value = (flags >> 5) & 0xE
    Reliability = 1 << 8, // When set, data will use lossy communications
    Verification = 1 << 9, // When set, data delivery will be verified
    Exception = 1 << 10, // When set, data will be published on change
    Resolution = 1 << 11, // When set, data will be down-sampled
    ResolutionTypeMask = 0x3000, // Mask for ResolutionType, value = (flags >> 12) & 0x2
    KeyAction = 1 << 14, // When set key is to be added; otherwise, removed
    ReservedFlag = 1 << 15 // Reserved flag
}
StateFlags; // sizeof(uint16), 2-bytes

```

Send Data Points Command

Data point packet commands are sent without the expectation of a response, as such data point packets can be transmitted over a lossy communications protocol, e.g., UDP, and thus are suitable for data channel functionality.


Detailed serialization of this packet is described in a different section. However, the general form of the structure looks like the following.

```

struct {
    SttpDataPoint[] points
}
SendDataPoints;

```

There are other custom encoding methods that can be optionally supported, but this encoding method is designed to catch all encoding cases.

 The data point packet commands are sent continuously after a successful `subscribe` command and will continue to flow for available measurements until a `unsubscribe` that unsubscribes from all measurements is issued.

Send Data Points Custom Command

A number of custom encoding methods will be supplied that will optimize encoding for special cases. These are specified in the appendix. These encoding methods are optional and are negotiated during the Negotiate Session stage.

```
struct {
    byte encodingMethod
    byte[] data
}
SendDataPointsCustom;
```

Runtime ID Mapping Command

Identifies which DataPointIDs are mapped to runtime IDs. Not all DataPointIDs must be mapped to runtimeIDs, however, the exact number that can be mapped are identified during the Negotiate Session phase.

```
struct {
    SstpPointID[] points
}
RuntimeIDMapping;
```

Negotiate Session Command

After a successful connection has been established, the publisher and subscriber shall participate in an initial set of negotiations that will determine the STTP protocol version and operational modes of the session. The negotiation happens with the `NegotiateSession` command code which must be the first command sent after a successful publisher/subscriber connection. The command is sent before any other commands or responses are exchanged so that the "ground-rules" for the communications session can be established. Once the session negotiations for the protocol version and operational modes have been established they must not change for the lifetime of the session.

Session negotiation is a multi-step process with commands and responses being sent by the publisher and subscriber until negotiation terms are either established or the connection is terminated because terms could not be agreed upon.

This command is broken up into sub commands. The sub commands include:

- Subcommands
 - `InitiateReverseConnection` - The connecting client desires to act as the server.
 - `GetAllInstances` - Request all named instances on the server.
 - `ChangeInstance` - Requests to change the instance connected to.
 - `SupportedFunctionality` - Tell the server what functions/versions are supported by your client.
 - `ChangeUdpCipher` - Indicates that the UDP cipher needs to be changed.

Protocol Version Negotiation

TODO: This has changed, but functionally still exists in the `SupportedFunctionality` command.

Future STTP protocol versions can include different session negotiation options, so the first session negotiation step is always to establish the protocol version to use. Immediately after connecting, the publisher must start the protocol version negotiation process by sending the `NegotiateSession` command to the subscriber that shall

contain information on the available protocol versions that the publisher supports. The subscriber shall be waiting for this initial publisher command; if the subscriber does not receive the command in a timely fashion (time interval controlled by configuration), the subscriber should disconnect.

The payload of the first `NegotiateSession` command sent by the publisher shall be an instance of the `ProtocolVersions` structure, defined as follows, that iterates the versions of the STTP protocol that are supported:

```
struct {
    uint8 count;
    Version[] versions;
}
ProtocolVersions;
```

- The `count` field defines the total number of elements in the `versions` field array.
- The `versions` field is an array of `Version` structures.

Since the current version of this specification only defines details for version 1.0 of STTP, the initial `NegotiateSession` command payload from the publisher shall be an instance of the `ProtocolVersions` structure with a `count` value of `1` and a single element `versions` array where `versions[0].major` is `1` and `versions[0].minor` is `0`.

When the first `NegotiateSession` command is received from the publisher, the subscriber must send either a `Succeeded` or `Failed` response for the `NegotiateSession` command indicating its ability to support one of the specified protocol versions.

If the subscriber can support one of the protocols specified by the publisher, the `Succeeded` response payload shall be an instance of the `ProtocolVersions` structure with a `count` of `1` and a single element `versions` array that indicates the protocol version to be used.

If the subscriber cannot support one of the protocols specified by the publisher, the `Failed` response payload shall be an instance of the `ProtocolVersions` structure filled out with the supported protocols. In case of failure, both the publisher and subscriber should terminate the connection since no protocol version could be agreed upon.

When a `Succeeded` response for the first `NegotiateSession` command is received from the subscriber, the publisher should validate the subscriber selected protocol version. If the publisher does not agree with the protocol version selected by the subscriber, the publisher shall send a `Failed` response for the `NegotiateSession` command with an empty payload and terminate the connection since no protocol version could be agreed upon. If the publisher accepts the subscriber selected protocol version, the negotiation will continue with the selection of operational modes.

After sending a `Succeeded` response to the first `NegotiateSession` command, the subscriber shall be waiting for either a `Failed` response from the publisher or the second `NegotiateSession` command; if the subscriber does not receive a command or response in a timely fashion (time interval controlled by configuration), the subscriber should disconnect.

Operational Modes Negotiation

TODO: This has changed, but functionally still exists in the `SupportedFunctionalty` command.

For version `1.0` of STTP, if the protocol version negotiation step succeeds, the next negotiation will be for the desired operational modes. The payload of the second `NegotiateSession` command sent by the publisher shall

be an instance of the `OperationalModes` structure, defined as follows, that iterates the supported string encodings, whether UDP broadcasts are allowed and the available stateful and stateless compression algorithms (see [compression algorithms](#)):

```
struct {
    uint16 udpPort;
    NamedVersions stateful;
    NamedVersions stateless;
}
OperationalModes;
```

- The `udpPort` field meaning depends on the usage context:
 - When sent with the publisher command payload, field is used to indicate publisher support of UDP. A value of zero indicates that UDP broadcasts are not supported and any non-zero value indicates that UDP broadcasts are supported.
 - When sent with the subscriber response payload, field is used to indicate the desired subscriber UDP port for data channel functionality. A value of zero indicates that a UDP connection should not be established for subscriber data channel functionality.
- The `stateful` field defines the `NamedVersions` representing the algorithms to use for stateful compression operations.
- The `stateless` field defines the `NamedVersions` representing the algorithms to use for stateless compression operations.

When the second `NegotiateSession` command is received from the publisher, the subscriber shall send either a `Succeeded` or `Failed` response for the `NegotiateSession` command indicating its ability to support a subset of the specified operational modes.

If the subscriber can support a subset of the operational modes allowed by the publisher, the `Succeeded` response payload shall be an instance of the `OperationalModes` structure with the specific values for the `encodings`, `udpPort`, `stateful` and `stateless` fields. The `encodings` field should specify a single flag designating the string encoding to use and both the `stateful` and `stateless` fields should define a `count` of `1` and a single element array that indicates the [compression algorithm](#) to be used where a named value of `NONE` with a version of `0.0` indicates that no compression should be used.

If the subscriber cannot support a subset of the operational modes allowed by the publisher, the `Failed` response payload shall be an instance of the `OperationalModes` structure filled out with the supported operational modes. In case of failure, both the publisher and subscriber should terminate the connection since no protocol version could be agreed upon.

When a `Succeeded` response for the second `NegotiateSession` command is received from the subscriber, the publisher should validate the subscriber selected operational modes. If the publisher does not agree with the operational modes selected by the subscriber, the publisher shall send a `Failed` response for the `NegotiateSession` command with an empty payload and terminate the connection since no operational modes could be agreed upon. If the publisher accepts the subscriber selected operational modes, then the publisher shall send a `Succeeded` response for the `NegotiateSession` command with an empty payload and the publisher will consider the session negotiations to be completed successfully.

After sending a `Succeeded` response to the second `NegotiateSession` command, the subscriber shall be waiting for either a `Succeeded` or `Failed` response from the publisher; if the subscriber does not receive a response in a timely fashion (time interval controlled by configuration), the subscriber should disconnect.

If the subscriber receives a `Succeeded` response for the `NegotiateSession` command from the publisher, the

subscriber will consider the session negotiations to be completed successfully.

Once operational modes have been established for a session, the publisher and subscriber must exchange any string based payloads using the negotiated string encoding as specified by the subscriber.

Secure Data Channel

When data channel functions that are operating over a lossy communications protocol, e.g., UDP, and command channel functions are operating over a reliable communications protocol, e.g., TCP, that has been secured with TLS, then the subscriber can request that data channel functions can be secured by issuing a `SecureDataChannel1` command.

The `SecureDataChannel1` command should only be issued when a lossy communications protocol, e.g., UDP, has been defined for data channel functions. If a subscriber issues the `SecureDataChannel1` command for a session that has not defined a lossy communications protocol for data channel functions, the publisher shall send a `Failed` response for the `SecureDataChannel1` command with a string based payload that indicates that data channel functions can only be secured when a lossy communications protocol has been established. This error condition should equally apply when UDP broadcasts are not supported by the publisher.

The `SecureDataChannel1` command should only be issued when command channel functions are already secured using TLS. If a subscriber issues the `SecureDataChannel1` command for a session with a command channel connection that has not been secured using TLS, the publisher shall send a `Failed` response for the `SecureDataChannel1` command with a string based payload that indicates that data channel functions can only be secured when command channel functions are already secured using TLS.

The `SecureDataChannel1` command should be issued prior to the `Subscribe` command to ensure data channel functions are secured before transmission of `DataPointPacket` commands. If a subscriber issues the `SecureDataChannel1` command for a session that already has an active subscription, the publisher shall send a `Failed` response for the `SecureDataChannel1` command with a string based payload that indicates that data channel functions cannot be secured after a subscription has already been initiated.

If data channel functions can be secured, the publisher shall send a `Succeeded` response for the `SecureDataChannel1` command with a payload that shall be an instance of the `DataChannelKeys` structure, defined as follows, that establishes the symmetric encryption keys and associated initialization vector used to secure the data channel:

```
struct {
    uint16 nonceLength;
    uint8[] nonce;
}
ChangeUdpCipher;
```

TODO: We also need a way to send the encryption key if UDP only.

- Both the server and the client specify a random number to prevent the key from being repeated or set to 000's
- The `key` field is a byte array computed from `SHA256(ServerNonce || ClientNonce)`.
- The `iv` field is the first 16 bytes of the byte array computed from `SHA256(ClientNonce || ServerNonce)`.

Upon the publisher sending the `Succeeded` response for the `SecureDataChannel1` command, all data function payloads for commands and responses sent by the publisher to the subscriber over the lossy communications protocol must be encrypted using the AES symmetric encryption algorithm with a key size of 256 using the specified subscriber key and initialization vector.

After sending a `SecureDataChannel` command to the publisher, the subscriber shall be waiting for either a `Succeeded` or `Failed` response from the publisher; if the subscriber does not receive a response in a timely fashion (time interval controlled by configuration), the subscriber should disconnect.

If the subscriber receives a `Failed` response for the `SecureDataChannel` command from the publisher, the subscriber should disconnect.

🔧 Failure responses from the publisher will either be from a configuration mismatch or an order of operations issue, STTP implementations should make subscribers aware of the possible exception causes so that the issue can be corrected.

Upon reception of a `Succeeded` response for the `SecureDataChannel` command from the publisher, the subscriber must take the received key and initialization vector and decrypt each payload received over the lossy communications protocol using the AES symmetric encryption algorithm with a key size of 256.

🔧 It is presumed that communications over a lossy communications protocol, e.g., UDP, will flow from the publisher to the subscriber. If an implementation of STTP is ever established such traffic would flow from the subscriber to the publisher over a lossy communications channel, then to be secured, this traffic would need to be encrypted by the subscriber and decrypted by the publisher.

Unsubscribe Command

TODO: This command has been replaced with a Subscribe, Remove, All command.

The subscriber shall issue an `Unsubscribe` with an empty payload to stop any existing data subscription.

Upon reception of the `Unsubscribe` command from a subscriber, the publisher must immediately cease publication of `DataPointPacket` commands to the specific subscriber that issued the command; also, the publisher shall send a `Succeeded` response for the `Unsubscribe` command with an empty payload. If for any reason the publisher cannot terminate the subscription, the publisher shall send a `Failed` response for the `Unsubscribe` command with a string based payload that describes the reason the subscription cannot be terminated.

After sending an `Unsubscribe` command to the publisher, the subscriber shall be waiting for either a `Succeeded` or `Failed` response from the publisher; if the subscriber does not receive a response in a timely fashion (time interval controlled by configuration), the subscriber should disconnect and not attempt to send further commands to stop the data subscription.

If the subscriber receives a `Failed` response for the `Unsubscribe` command from the publisher, the subscriber should disconnect and not attempt to send further commands to stop the data subscription.

Upon reception of a `Succeeded` response for the `Unsubscribe` command from the publisher, the subscriber should consider any cached signal mapping previously received from the publisher to now be invalid - accordingly any allocated memory for the cache should now be released.

🔧 With reception of the `Succeeded` response for the `Unsubscribe` command the subscriber can be assured that the publisher has stopped sending further `DataPointPacket` commands, however, STTP implementations should anticipate that some data packets could still arrive depending on how much data was already queued for transmission. This may be more evident when a lossy communications protocol, e.g., UDP, is being used for data channel functionality and the `Succeeded` response for the `Unsubscribe` command is received on a reliable communications protocol, e.g., TCP.

Bulk Transport Command

This command has the ability of sending large blocks of data over STTP.

This command is broken up into sub commands. The sub commands include:

- Subcommands
 - `BeginSend` - Indicates a new large block of data is on its way.
 - `SendFragment` - Indicates that a new fragment of data is being sent.
 - `CancelSend` - Indicates that a send operation is being canceled.

NoOp Command


When data channel functions are operating over a lossy communications protocol, e.g., UDP, and command channel functions are operating over a reliable communications protocol, e.g., TCP, then command channel activity may remain quiet for some time. To make sure the connection for the command channel is still established the `NoOp` command allows for a periodic test of connectivity.

The `NoOp` command shall be initiated by either the publisher or subscriber. For this functional description the initiator of the command will be called the *sender*, whereby the other party will be the *receiver*. The `NoOp` command is always sent with an empty payload and is designed to be sent over a reliable communications channel, e.g., TCP, on a configurable schedule.

Upon reception of the `NoOp` command from a sender, the receiver shall send a `Succeeded` response for the `NoOp` command with an empty payload.

After sending a `NoOp` command to the receiver, the sender shall be waiting for a `Succeeded` response from the receiver; if the sender does not receive a response in a timely fashion (time interval controlled by configuration), the sender should disconnect. If the sender uses a client-style socket, the sender should reestablish the connection cycle.

Upon reception of a `Succeeded` response for the `NoOp` command from the receiver, the sender should consider the connection valid and reset the timer for the next `NoOp` test.

 For implementations of STTP the `NoOp` command will be used to test that the reliable communications channel is still available. Implementations will check for exceptions that occur during transmission of the command as well as timeouts due to lack of responses, in either case the communications channel can be considered failed and placed back into a connection cycle state.

Responses

The following table defines the responses to commands that can be sent by STTP.

Code	Type	Source	Description
0x80	GetMetadataSchemaResponse	Publisher	Sends the schema for the metadata to the Subscriber
0x81	GetMetadataResponse	Publisher	Sends metadata results to the Subscriber.
0x82	NegotiateSessionResponse	Publisher	Responds to negotiate session commands.
0x83	RequestSucceeded	Any	Command request succeeded.
0x84	RequestFailed	Any	Command request failed. Response error payload, if any, included.

Get Metadata Schema Response

Responds with the schema for the metadata

```
struct {  
    MetadataSchema schema;    //The command code that succeeded.  
}  
GetMetadataSchema;
```

Get Metadata Response

Responds with the metadata.

- Subcommands
 - `VersionNotCompatible` - If SchemaVersion does not match the current one, or if revision is too old to do an update query on.
 - `DefineTable` - Defines the response Table.
 - `DefineRow` - Defines a row of the data.
 - `UndefineRow` - For update queries, indicates this row should be removed if it exists.
 - `Finished` - Indicates that the streaming of the table has completed.

Negotiate Session Response

Responds to the NegotiateSession command.

- Subcommands
 - `ChangeInstanceSuccess` - Changes the active instance of the connection.
 - `ChangeUdpCipherResponse` - Returns data and agrees to change the UDP cipher.
 - `DesiredOperation` - Reply to SupportedFunctionality, indicates the selected mode of operation.
 - `InstanceList` - The list of all instances this server has.
 - `ReverseConnectionSuccess` - Transfers the role of server to the client.

Request Succeeded

A response with a type `Succeeded` is intended to represent a successful reply for a command function. See associated [command code](#) for proper response.

```
struct {  
    CommandCode command;    //The command code that succeeded.  
    string Reason;          //A user friendly message for the success, can be null.  
    string Details;         //A not so friendly message more helpful for troubleshooters.  
}  
RequestSucceeded;
```

Request Failed

A response with a type `Failed` is intended to represent a failure reply for a command function. See associated [command code](#) for proper response.


```
struct {  
    CommandCode command;    //The command code that failed.  
    bool TerminateConnection; //Indicates that the connection should be terminated for a failure.  
    string Reason;          //A user friendly message for the failure, can be null.  
    string Details;         //A not so friendly message more helpful for troubleshooters.  
}  
RequestSucceeded;
```

Data Point Structure

When a subscriber has issued a [subscribe command](#) to its publisher for select set of data points, the publisher will start sending [data point packet commands](#) each with a payload of several data point values serialized using the `DataPoint` structure, defined as follows:

```
struct {
    int32 runtimeID;           // -1 if not specified, can optionally be sent instead of `id`.
    SttpValue id;              // A point Identifier.
    SttpValue timestamp;       // A timestamp, SttpTimestamp is highly recommended for this field but
    SttpValue value;           // The single value that represents this Data Point.
    uint64 quality;            // Unstructured quality bits. Quality bits use may be specified in te
    SttpValue ExtendedData;    // Additional data that can be sent if `value` is insufficient.
}
DataPoint;
```

The actual number of `DataPoint` structures contained in the data point packet command depends the configured maximum payload size and the serialized size of the data point structures, see [Figure 6](#).

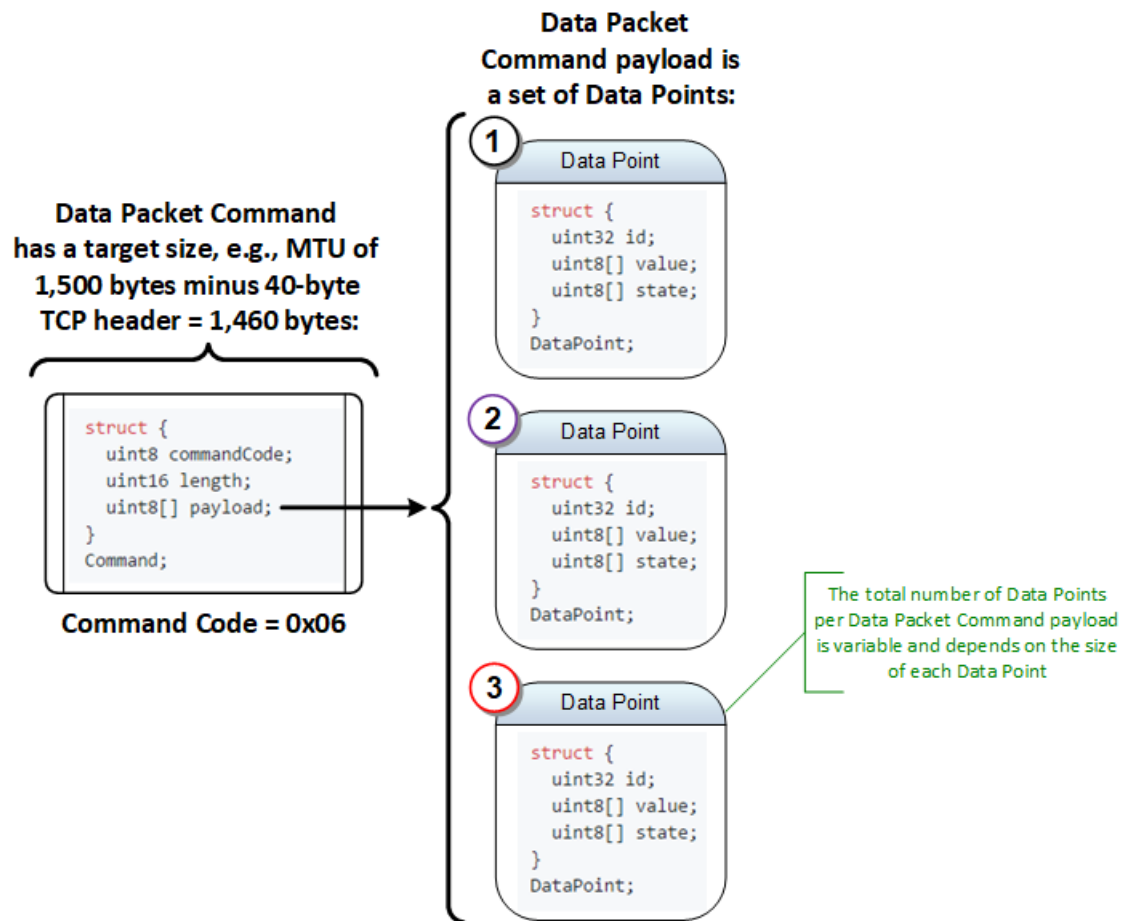


Figure 6

i The maximum size of a `DataPoint` structure instance is unspecified, but controlled indirectly at the wire level protocol. With simple encoding techniques this size can be reduced down to a few bytes for most value types.

Runtime ID

Runtime ID's are negotiated with the connection and are the default value type in the Data Point Structure. The runtime ID is used to associate a group of communications under a single STTP connection.

While the normal use case is to use RuntimeIDs, for systems that have an indefinite number of IDs, it's not practical to map every point to a Runtime ID. In this case, it's allowed to send the identifier with the measurement.

If no runtime ID is used -1 should be sent

Data Point Identifier

When identifying a Data Point, one of 4 mechanics are encouraged to identify the source of the time series data. STTP expects a ID to be unique per data point. Common ids include:

- [Guid] - Some kind of integer based identifier.
- [String] - This is commonly referred to as a tag in a time series databases.
- [SttpMarkup] - Essentially this is a connection string that combines a set of unique identifiers.

If using a template to standarize metadata the template may specify additional constraints on the ID. See [Appendix F - STTP Templates](#) for example templates

STTP Value Types

The data types available to a `DataPoint` are described in the `ValueType` enumeration, defined below:

```
enum {
    Null = 0,           // 0-bytes
    Int64 = 1,          // 8-bytes
    Single = 2,         // 4-bytes
    Double = 3,         // 8-bytes
    SttpTime = 4,       // Universal Time with Leap Seconds
    Bool = 5,           // 1-byte
    Guid = 6,           // 16-bytes
    String = 7,         // Limit defined in NegotiateSession
    SttpBuffer = 8,     // Limit defined in NegotiateSession
    SttpMarkup = 9,     // An array of SttpValue. Up to 255 elements.
    SttpBulkTransport = 10 // A pointer to a large object. Data must be requested as a seperate co
}
ValueTypeCode; // sizeof(uint4), 1-nibble
```

- `Null` : No space occupied
- `Int64` : [64-bit Signed Integer](#) (8-bytes, big-endian)
- `Single` : [32-bit Single Precision Floating Point](#) (4-bytes, per [IEEE 754-2008](#))
- `Double` : [64-bit Double Precision Floating Point](#) (8-bytes, per [IEEE 754-2008](#))
- `SttpTime` : [Time as Timestamp](#) (8-bytes, see [data point timestamp](#))
- `Bool` : [Boolean as 1-bit](#) (1-bit, zero is `false` , 1 is `true`)
- `Guid` : [Globally Unique Identifier](#) (16-bytes, big-endian for all components)
- `String` : [Character String as StringValue](#) (encoding is UTF8)
- `SttpBuffer` : [Untyped Data Buffer as BufferValue](#)
- `SttpMarkup` : [Untyped Data Buffer as BufferValue](#)
- `SttpBulkTransport` : [Untyped Data Buffer as BufferValue](#)

Encoding Methods

When encoding each of these values, a 4-bit `ValueTypeCode` will be written first, then the value itself will be written. The 4-bit prefix can be optimally eliminated, but a separate encoding algorithm must make that determination.

All serialization will occur through the `Bit-Byte-Block`. So reference that section for additional serialization details.

Unless specifically called out below, the types are serialized using the `BitByteBlock` corresponding type.

Int64

These values are variable length encoded where leading 0's are not stored. In order to prevent a value of -1 from consuming a full 8 bytes, this value will undergo a lossless transformation of its bits so it has leading 0's. The transformation is described in the following code:

Encoding: rotate left 1, then inverts bits 1-63 if bit 0 is 1.

Decode: invert bits 1-63 if bit0 is 1, then rotate right 1.

```
long PackSign(long value)
{
    if (value >= 0)
        return value << 1;
    return (~value << 1) + 1;
}

long UnPackSign(long value)
{
    if ((value & 1) == 0)
        return (value >> 1) & long.MaxValue;
    return (~value >> 1) | long.MinValue;
}
```

After Packing the value, it is serialized using `Write8BitSegments`.

SttpTime

`SttpTime` is a specially encoded timestamp based on Microsoft's .NET `DateTime` field, however, a leap second can be added at the end of every minute. There are approximately 145 billion seconds of space unused in the first 62-bits of the `DateTime` field. However, there are only 5 billion distinct minutes between year 1 and 9999. The space above `DateTime.MaxValue` has been allocated to a 61st second.

`SttpTime` is encoded/decoded as a typical `int64` consuming 8 bytes (as opposed to a variable length `SttpValueTypeCode.Int64`)

SttpBuffer

This value contains only a byte buffer, and is serialized using `BitByteBlock.Write(byte[] data);`

SttpMarkup

At it's core, a `SttpMarkup` is only a byte buffer, and is serialized using `BitByteBlock.Write(byte[] data);`

See `SttpMarkup` section for more details on how the internals of this object are serialized.

SttpBulkTransport

This value is a pointer type, and contains the following fields.

```
struct {  
    SttpValueTypeCode fundamentalType; // The type of the underlying data.  
    Guid bulkTransportID                // The ID that can be used to request this data.  
    long length;                        // The length of the data.  
}  
SttpBulkTransport;
```

And is serialized as:

- Bits4(fundamentalType);
- Guid(bulkTransportID);
- Int64(length);

Data Point Encoding Types

STTP supports various options for encoding data points within data packet commands. Different levels of encoding functionality allows data to be sent more efficiently and consume less space.

i An STTP publisher implementation is in control of which types of encodings it supports. Encoding is a different activity than compression; compression algorithms often require a specific type of base encoding.

Basic Encoding

Structure definitions that represent the basic format of data points as serialized on the wire are as described in the [Data Point Structure](#) section. Basic encoding serializes data elements in their native format without any attempt to reduce the size of the data, except to only include necessary state information. All implementations of STTP must be able to support basic encoding.

The size of the `DataPoint.value` with basic encoding depends on its type as defined in the `DataPointKey.type`. The size and content of the `DataPoint.state` is determined by the `DataPointKey.flags`, see the [runtime ID mapping command](#), these flags control the information that is included in the encoded state.

Optional States

- **Timestamp** - the timestamp value is only included in the `DataPoint.state` data when the `DataPointKey.flags` includes the `StateFlags.Timestamp` flag. When included, the `Timestamp` structure must be the first value serialized into the `DataPoint.state` data.
- **Time Quality Flags** - the time quality flags are only included in the `DataPoint.state` data when the `DataPointKey.flags` includes the `StateFlags.TimeQuality` flag. The `TimeQualityFlags` must be serialized into the `DataPoint.state` data in big-endian order following any defined timestamp. If no timestamp is defined for the `DataPoint.state` data, i.e., the `DataPointKey.flags` defines `Timestamp` as `0`, then the `TimeQualityFlags` should not be serialized into the `DataPoint.state` data.
- **Data Quality Flags** - the data quality flags are only included in the `DataPoint.state` data when the `DataPointKey.flags` includes the `StateFlags.DataQuality` flag. The `DataQualityFlags` must be serialized into the `DataPoint.s` data in big-endian order following any defined time quality flags. n If no time quality flags are defined for the `DataPoint.state` data, i.e., the `DataPointKey.flags` defines `Timestamp` as `0`, then the `DataQualityFlags` must be the first value serialized into the `DataPoint.state` data.
- **Sequence Identifier** - the sequence identifier, which is defined as a `uint32`, must be serialized into the `DataPoint.state` data in big-endian order following any defined `DataQualityFlags`, `TimeQualityFlags` or timestamp. If no timestamp is defined for the `DataPoint.state` data, i.e., the `DataPointKey.flags` defines `Timestamp` as `0` and no `DataQualityFlags` is defined for the `DataPoint.state` data, i.e., the `DataPointKey.flags` does not include the `StateFlags.DataQuality` flag, then the sequence identifier must be the first value serialized into the `DataPoint.state` data.
- **Fragment Number** - the fragment number, which is defined as a `uint32`, must be serialized into the `DataPoint.state` data in big-endian order following any defined sequence identifier, `DataQualityFlags`, `TimeQualityFlags` or timestamp. If no timestamp is defined for the `DataPoint.state` data, i.e., the `DataPointKey.flags` defines `Timestamp` as `0` and no `DataQualityFlags` is defined for the `DataPoint.state` data, i.e., the `DataPointKey.flags` does not include the `StateFlags.DataQuality` flag, and no sequence identifier is defined for the `DataPoint.state` data, i.e., the `DataPointKey.flags` does not include the `StateFlags.Sequence` flag, then the fragment number must be the first value serialized into the `DataPoint.state` data.

Compact Encoding

⚠ This mode was enabled in GEP to accommodate a smaller payload size. Specifically timestamps were transmitted as an offset to a base time that maintained two states. Also, GEP focused on 4-byte single-precision floating point numbers only. This along with some compact flags for quality and a 16-bit runtime ID got per data point size to around 9-bytes. It is expected that this mode of operation could still have value when data packets are sent over UDP, however, TCP transmissions would be best served using TSSC because of the gains that can be had with that algorithm.

Fixed Size Encoding


In order to accommodate advanced compression algorithms, e.g., [TSSC compression](#), an alternate data point encoding is used where values are serialized using the `FixedSizeDataPoint` structure, defined below. The `FixedSizeDataPoint` structure aligns data on a word boundary and has a fixed size, so no fields are considered optional. Instead when the `StateFlags` call for an excluded field, the `FixedSizeDataPoint` structure will simply zero out the values for the field which allows the repeating values to be *compressed out* of the final result.

```
struct {
    uint32 id;
    uint64[8] value; // Bytes of the value
    uint64 time1;    // Lower 8 bytes of the time, used for Timestamp.seconds
    uint64 time2;    // Upper 8 bytes of the time, used for Timestamp.fraction
    TimeQualityFlags timeQualityFlags;
    DataQualityFlags dataQualityFlags;
    uint32 sequence;
    uint32 fragment;
    uint8 length;
}
FixedSizeDataPoint;
```


Data Point Characteristics

STTP will allow the ability to define delivery and quality of service characteristics for each data point made available for publication. These characteristics include priority, reliability, verification, exception and resolution.

The publisher is in full control of what per data point delivery characteristics are allowed. The transport layers in use for the connection will also dictate the availability of some characteristics, e.g., reliability. Regardless, the subscriber can always request a specific set of per data point delivery characteristics, but these may be denied by the publisher.

 Once defined, reference associated command / response details that define the negotiations for data point delivery characteristics.

The delivery characteristics for each data point have been defined to fit within a single byte. Default delivery characteristics will be assumed during subscription initialization for data points when none are otherwise defined, i.e., data point delivery characteristic flags value will be 0x00.

 As an optimization, subscribers need to be able to group multiple delivery characteristic requests into a single message with an optimized payload size since request could be sizable for a very large number of data points. Same goes for any publisher response payloads.

Since publisher will be able to reject, en masse, subscriber requested data point delivery characteristics, there will need to be a way in the publisher configuration to define the required and allowable characteristics for each data point.

Another consideration is that it may be desirable that these configurations be changeable per subscriber. For example, user may want to require that a subscriber with a known slow connection to be forced to use an alternate lossy data communications channel for streaming data point values that can tolerate loss, but allow command communications channel for all data for subscribers using more reliable connections.

Publisher configuration could be greatly simplified (possibly reduced) if data points can be assigned as required and allowable characteristics based on some automated high-level data point classification, such as, data points that can tolerate loss (streaming) or data points that require verification (control / critical).

Overall thoughts on data point delivery characteristics are that since publisher is exclusively in control of delivery requirements from both a "required" and "allowed" perspective – to reduce negotiations, publisher should provide the required and allowed characteristics with the meta-data that is provided to the subscriber – this way subscriber won't inadvertently request something that is not allowed.

Priority Characteristic

Per data point subscriber request will assign data point level routing priority at the publisher. All priority values will be specific to each subscription.

Flag Definition

Three-bit value defining 8 priorities, i.e., 0 to 7, where 0, default, is the lowest priority and 7 is the highest priority. Note that value 7 is a reserved system-level priority, leaving a total of 7, ranging from 0 to 6, user-level priorities. Data point priority value occupies bits 0 to 2 of the data point delivery characteristic flags where the unsigned 3-bit integer is encoded in big-endian order.

Rights and Responsibilities

Publisher will have the right to reject subscriber requested priority levels. If publisher rejects requested priority

levels, then failure response to subscriber will include assigned levels for each data point so that subscriber can accept and update its run-time priority levels with those proposed by publisher or otherwise terminate the connection.


Subscriber can request desired priority levels but is subject to publisher assigned levels. A common use case may be that data points with the verification characteristic enabled will also be requested to use higher priority levels. If the subscriber does not agree with assigned data point priority levels then, with appropriate response before termination, the subscriber will close the connection.

Recommended Operational Statistics

- Publisher will maintain overall and per-subscriber statistical count of how many data points are configured at each priority.
- Publisher will maintain overall and per-subscriber statistical count of how many data points have been published at each priority.
- Subscriber will maintain statistical count of how many data points are configured at each priority.
- Subscriber will maintain statistical count of how many data points have been received at each priority.

Reliability Characteristic

Per data point subscriber request would have publisher send data point values over reliable command communications channel (e.g., TCP) or send without retransmission over lossy data communications channel (e.g., UDP). Reliability flag will be ignored when there is no defined alternate data communications channel.

 If a spontaneous, unicast only data publication mode is supported by STTP, then need to address that mode of operation here. For a unicast only publication mode, any reliability characteristics published as part of the configuration would all need to be set to lossy mode.

Flag Definition

Single bit value where 0, default, is *send data point over the reliable command communications channel* - and 1 is *send data point over the lossy data communications channel*. Data point reliability value occupies bit 3 of the data point delivery characteristic flags.

Rights and Responsibilities

Publisher will have the right to reject subscriber requested reliability values. If publisher rejects requested reliability values, then failure response to subscriber will include assigned values for each data point so that subscriber can accept and update its run-time reliability values with those proposed by the publisher or otherwise terminate the connection.

Subscriber can request desired reliability values but is subject to publisher assigned values. A common use case may be that typical streaming data that can tolerate loss be restricted by the publisher to a lossy data communications channel, e.g., UDP, to reduce possibility of command communications channel queuing over slow or noisy connections. If the subscriber does not agree with assigned data point reliability values then, with appropriate response before termination, the subscriber will close the connection.

Note that if publisher requires that any of the subscribed data be published over a lossy data communications channel and the subscriber has not defined one, the publisher, with appropriate notification of issue to subscriber, will terminate the connection.

Recommended Operational Statistics

- Publisher will maintain overall and per-subscriber statistical count of how many data points are

configured for both command communications channel and data communications channel.


- Publisher will maintain overall and per-subscriber statistical count of how many data points have been published for both command communications channel and data communications channel.
- Subscriber will maintain statistical count of how many data points are configured for both command communications channel and data communications channel.
- Subscriber will maintain statistical count of how many data points have been received for both command communications channel and data communications channel.


Verification Characteristic

Per data point publisher assigned characteristic will inform subscriber that a reply must be provided with receipt of data point delivery. Failure to receive receipt, within configured timeout of sender, will be exposed via API so that host application can manage any appropriate action, e.g., exception logging and/or queue for retry. It is expected that verified data points only be used for sending critical data, either from subscriber to publisher or publisher to subscriber, e.g., a control value that will require verification of receipt.

 Once defined, reference associated command / response details that define the negotiations for data point verification.

Data point verification functions must exist in both publisher and subscriber. In the case of the subscriber, critical data points sent from publisher that are marked with a verification characteristic must be replied to with a verification message upon receipt of value. For the publisher, data points can be made available that are updatable by the subscriber, e.g., write registers or data points used for control “ when these data points are marked with a verification characteristic, the publisher will reply to subscriber with a verification message upon receipt of value.

 End users managing publisher configuration should be made aware of the implications of requiring data point delivery verification, e.g., increased bi-directional bandwidth requirements as well as induced data point latencies because of round-trip confirmation messages “ this awareness is needed so that verification characteristics are applied judiciously. For example, high-speed streaming data would not be a good candidate for delivery verification.

 If a spontaneous, unicast only data publication mode is supported by STTP, then need to address that mode of operation here. For a unicast only publication mode, no form of verification could be supported.

Flag Definition

Single bit value where 0, default, is data point received receipt is not required and 1 is data point received receipt is required. Data point verification value occupies bit 4 of the data point delivery characteristic flags.

Rights and Responsibilities

Publisher has full authority over determination of which data points require verification. Any verification flags that may be specified by subscriber during data point delivery characteristic requests will be ignored. Subject to rights verification of subscriber to send data points back to publisher, any data points destined to publisher that are marked for verification must respond with a verification receipt back to subscriber upon successful delivery.


Subscriber must reply to publisher upon receipt of data points that are marked for verification. If the subscriber does not agree with the volume of subscribed data points that require verification then, with appropriate response before termination, the subscriber can terminate the connection. For example, if publisher specifies verification for a large volume of the subscribed data points, this may exceed subscriber's configured upload bandwidth and connection will need to be terminated.


Recommended Operational Statistics

- Publisher will maintain overall and per-subscriber statistical count of how many data points are configured for delivery verification.
- Publisher will maintain overall and per-subscriber statistical count of how many data points have been published with delivery notification.
- Publisher will maintain overall and per-subscriber statistical count of how many delivery receipts have been sent to subscribers.
- Subscriber will maintain statistical count of how many data points are configured for delivery verification.
- Subscriber will maintain statistical count of how many data points have been published with delivery notification.
- Subscriber will maintain statistical count of how many delivery receipts have been sent to publisher.

Exception Characteristic


Per data point subscriber request would have publisher either always send data points when they are made available or only send data points when they change as compared to last published value, i.e., on exception. Where applicable by data point value primitive type, i.e., numeric types, the exception can be restricted to a deviation of last published value. Exceptions with specified deviations for numeric types would be calculated as the absolute value of the last published data point value minus the current data point value being greater than or equal to the specified deviation, e.g.: `canPublish = abs(lastValue - currentValue) >= deviation`. The default deviation for any numeric primitive type will always be zero such that any change in value will trigger a publication. For any data points with values that are non-numeric primitive types, publisher will always send value when it changes, i.e., no deviation logic will be applied when sending by exception for non-numeric primitive data types.

 Primitive data types need a clear classification of being "numeric" in order for exception characteristic to function properly.

 JO: Just for your consideration, in case you think this might be useful. SEL applies this "update by exception" rule by default for many tag types within the logic engine of our automation controller product and are referred to as "Deadbands". The behavior is the same as you've described in the paragraph above with one addition. A second setting called "Zero Deadband" is presented which further defines the exception characteristic. The exception condition would then be something like, e.g.: `'canPublish = (abs(lastValue - currentValue) >= Deadband) AND currentValue > ZeroDeadband'` This could be helpful in accounting for different modes of operation (testing/precommissioning/low level noise vs nominal measurements).

Per data point deviation for numeric types will need to be accommodated in subscription request - this is too large to fit within single byte characteristic flags.

As an optimization, deviation data should only be sent when exception characteristic is requested. Also, subscribers need to be able to group multiple delivery characteristic requests into a single message with an optimized payload size since request could be sizable for a very large number of data points. Specifying deviation based on a data point classification would be useful.

 If a spontaneous, unicast only data publication mode is supported by STTP then for a unicast only publication mode, no form of subscriber specified exception handling could be supported - receiver would simply be subject to what was provided.

Flag Definition

Single bit value where 0, default, is publisher will send data points when made available and 1 is publisher will only send data points on exception. Data point exception value occupies bit 5 of the data point delivery characteristic flags.

Rights and Responsibilities

Publisher must respect subscriber requested exception characteristics. If publisher cannot fulfill subscriber subscription request for specified exception characteristics, e.g., based on volume, then, with appropriate notification of issue to subscriber, publisher will terminate the connection.


Subscriber can request desired data point exception characteristics to reduce data reception volume with the expectation that if subscription to publisher succeeds, requested exception characteristics will be respected.


Recommended Operational Statistics

- Publisher will maintain overall and per-subscriber statistical count of how many data points are configured with exception based delivery.
- Publisher will maintain overall and per-subscriber statistical count of how many data points have been published with exception based delivery.
- Subscriber will maintain statistical count of how many data points are configured with exception based delivery.
- Subscriber will maintain statistical count of how many data points values have been received with exception based delivery.

Resolution Characteristic


Per data point subscriber request would have publisher either always send data points at full resolution or with down-sampling. Down-sampling options include latest, closest, best-quality and filtered.

 JRC: Need to carefully consider the pros and cons of this characteristic - especially the options. While extremely valuable, much energy could be spent on this with limited value in the final implementation. Filtering option is a tricky industry / data type specific thing. May need to be prescriptive in reference implementations / API that it can provide custom down-sampling functions.

 Per data point down-sampling resolution will need to be accommodated in subscription request. As an optimization, subscribers need to be able to group multiple delivery characteristic requests into a single message with an optimized payload size since request could be sizable for a very large number of data points. Specifying down-sampling resolution per subscription or per data point classification would be useful.

Filtering options are expected to be very lightweight and non-intrusive to make sure down-sampling does not adversely impact publisher performance. Even so, publisher should reserve the right to reject a filtered request and suggest something more lightweight, e.g., latest value.

It is expected that implementation will be a function of data point value primitive type, e.g., a simple average where applicable for numeric types. For non-numeric types and digital style values, like flags, a major filter will be needed. For synchrophasors, phase angles will need to be unwrapped, averaged then wrapped to provide an accurate average.

 If a spontaneous, unicast only data publication mode is supported by STTP then for a unicast only publication mode, no form of subscriber specified down-sampling could be supported - receiver would simply be subject to what was provided.

Flag Definition

Single bit value where 0, default, is publisher will send data points at full resolution and 1 is publisher will send data points at a down-sampled resolution. Data point resolution value occupies bit 6 of the data point delivery characteristic flags. Two-bit value defining 4 down-sampling options, i.e., 0 to 3, where 0, default, is latest data point, 1 is data point that is closest to publication timestamp for target down-sampled resolution, 2 is data point that has the best quality and 3 is default configured filter for the data point classification, e.g., average. Data point resolution down-sampling option occupies bits 7 and 8 of the data point delivery characteristic flags where unsigned 2-bit integer is encoded in big-endian order.

Rights and Responsibilities

Publisher must respect subscriber requested resolution characteristics when down-sampling resolution is requested, however, publisher has the right to reject subscriber requests for full resolution data or the type of resolution requested, for example, publisher may only allow non-filter based options for down-sampling to reduce loading. If publisher cannot fulfill subscriber subscription request for specified down-sampling characteristics or if publisher rejects requests for full resolution data or down-sampling options, then failure response to subscriber will include the proposed resolution characteristics for each data point so that subscriber can accept and update its run-time resolution values with those suggested by publisher or otherwise terminate the connection.

Subscriber can request desired data point resolution characteristics to reduce data reception volume with the expectation that if subscription to publisher succeeds, requested down-sampling characteristics will be respected. If publisher rejects requested characteristics, subscriber can expect that proposed resolution characteristics by the publisher will still provide down-sampling. If the subscriber does not agree with the proposed publisher resolution characteristics then, with appropriate response before termination, the subscriber will close the connection.

Recommended Operational Statistics:

- Publisher will maintain overall and per-subscriber statistical count of how many data points are configured with down-sampled delivery.
- Publisher will maintain overall and per-subscriber statistical count of how many data points have been published with down-sampled delivery.
- Subscriber will maintain statistical count of how many data points are configured with down-sampled delivery.
- Subscriber will maintain statistical count of how many data points have been received with down-sampled delivery.

Metadata

Metadata is exchanged in STTP as a table of records with attributes. The complete list of tables available from an STTP publisher may be requested over the command channel. When requesting all of the tables, a structure is returned as follows:

Table Types

Three types of tables are defined in STTP.

- **DataPoint Table** - The DataPoint Table conveys metadata related to an STTP data point. Each publisher shall maintain zero or one DataPoint Table. The name of the table shall be 'DataPoint'. The publisher shall maintain one unique record with the DataPoint Table for each data point defined.

TO DO: Define complex data structure and complex data structure mapping in definitions section. A CDSM may be either 'built-in' or 'user-defined'. 'Built-in' CDSMs may differ by industry. In the electric power industry, an example of a 'built-in' CDSM is a phasor.

- **CDSM Table** - A CDSM Table conveys metadata about a complex data structure. A publisher may maintain zero or more CDSM tables. A CDSM table shall only describe a CDSM defined at the publisher, and each record within the CDSM Table shall uniquely describe a corresponding mapping. An example of a CDSM in the transportation industry may be 'location', which is defined with two floating point values named 'latitude' and 'longitude'. Carrying forward this example, the description attribute for a record within the Position Table might be, 'Location of Truck #42'.
- **Resource Table** - A Resource Table conveys metadata related to a resource available in the publisher's asset base. A publisher may maintain zero or more resource tables to describe the desired asset hierarchy. A resource is any asset, whether hardware, software or physical, that relates to a data point transmitted over the wire. The simplest example of a resource is a sensor, or the transducer used to digitize a measured value.

A maximum of 2^{16} tables in any combination of the allowable types are permitted.

Commands

Metadata commands are encapsulated into a Refresh Metadata packet. These commands are as follows.

Note: these commands describe what is required to make the server side metadata look like the client side metadata. Additional synchronization needs to occur at the client side API when synchronizing with it's main repository.

- **Response Publisher to Subscriber**
 - **UseTable** - Changes the active table
 - int tableIndex
 - **AddTable** - Adds or Replaces a table if it already exists.
 - Guid majorVersion,
 - long minorVersion,
 - string tableName,
 - TableFlags flags
 - **AddColumn** - Adds a column.
 - int columnIndex,

- string columnName,
- ValueType columnType
- AddValue - Adds or updates a value. Deleting a value would be to assign it with null.
- int columnIndex,
- int rowIndex,
- byte[] value
- DeleteRow - Removes an entire row of data.
- int rowIndex,
- TableVersion - Indicates what the current version of a table is.
- int tableIndex
- Guid majorVersion,
- long minorVersion,
- AddRelationship - Adds a table relationship. Sometimes known as a foreign key relationship.
- int tableIndex
- int columnIndex,
- int foreignTableIndex
- Request Subscriber to Publisher
 - GetTable - Requests metadata from the specified table.
 - int tableIndex
 - int columnListCount
 - int[] columnIndexList
 - int filterExpressions
 - string[] filterExpressionStrings
 - SyncTable - Requests that the specified table is synchronized with the local copy. MajorVersion == Guid.Empty if the local table is blank.
 - int tableIndex
 - Guid majorVersion
 - long minorVersion
 - int columnListCount
 - int[] columnList
 - SelectAllTablesWithSchema - Gets all of the tables with their columns
 - GetAllTableVersions - Gets the version information for every table the user has access to.

Attribute Value Types

When defining each attribute, it is important to identify the type of data that is expected in that field. The wireline protocol itself will not enforce these requirements, but rather provides encoding mechanisms for transporting the data

and rules for how items can be converted to the desired type.

Encoding

When attributes are serialized, the value field must be encoded using one of the following encoding types:

Code	Type	Description
0x00	Null	A null value.

0x01	String	A UTF8 encoded string
0x02	Single	A 32-bit floating point number encoded Big Endian
0x03	Double	A 64-bit floating point number encoded Big Endian
0x04	Decimal	A 128-bit floating point number encoded Big Endian
0x05	Int32	A 32-bit integer number encoded Big Endian
0x06	Int64	A 64-bit integer number encoded Big Endian
0x07	Guid	A 128-bit GUID encoded Big Endian
0x08	Ticks	A 64-bit date/time value encoded Big Endian
0x09	Binary	An array binary values
0x0A	Boolean	A boolean value

Defining

The list below defines how the measurement fields can be restricted and what types are permitted under each restriction.

- Integer
 - Supported Types: Null | Single | Double | Decimal | Int32 | Int64
- Float
 - Supported Types: Null | Single | Double | Decimal | Int32 | Int64
- Date
 - Supported Types: Null | Ticks
- Time
 - Supported Types: Null | Ticks
- Date Time
 - Supported Types: Null | Ticks
- Duration
 - Supported Types: Null | Ticks
- Boolean
 - Supported Types: Null | Boolean
- Binary
 - Supported Types: Null | Binary
- String
 - Supported Types: All since all types can be represented as a string.
- Guid
 - Supported Types: Null | Guid

DataPoint Table Structure

For the DataPoint Table, the record identifier will correspond to the ID of the respective data point. The following table defines a minimal list of attributes associated with a data point.

Attribute Name	Attribute Value Type	Description
PointID	Guid	The GUID associated with the data point.

CDSM Table Structure

It is not mandatory for the publisher to maintain a CDSM Table for every CDSM defined by the publisher. When the publisher optionally defines metadata for a CDSM, the table must contain the following minimal set of attributes.

Attribute Name	Attribute Value Type	Description
CDSMID	Guid	The GUID associated with the CDSM.

Resource Table

It is not mandatory for the publisher to maintain Resource Tables. When the publisher optionally defines metadata for resources, the table must contain the following minimal set of attributes.

Attribute Name	Attribute Value Type	Description
ResourceID	Guid	The GUID associated with the resource.

Dataset Filtering

Note: These may end up being client side filters to simplify the wireline protocol and the burden on the server side API.

- Format of expressions that work against metadata
 - SQL style expressions
 - Regex style expressions
- Application of expressions
 - Metadata reduction (by subscriber)
 - Data point access security

Dataset Versioning

- Versioned
- Difference based publication

Dataset Serialization

- Serialization for transport
 - Publisher reduction by access rights and diff-version
 - Subscriber reduction by filter expression
- Serialization to local repository
 - Merging considerations
 - Conflict resolution
 - Ownership control

Compression

Compression algorithms used with STTP can be either stateful, i.e., the compressor maintains its state through all compressed records, or stateless, i.e., the compressor compresses each data packet independently.

Stateful compression algorithms provide the best possible compression for STTP data transmission but require use of a reliable transport protocol, e.g., TCP. Stateless compression methods are required when a lossy transport protocol is being used for data transmission, e.g., UDP.

Compression Algorithms

STTP is designed so that new compression algorithms can be implemented and used without requiring revisions to the specification. To accommodate this, compression algorithms are negotiated, by text name and numeric version, after a connection is established along with other operational modes for the session. See [session negotiation](#) for more details.

Compression algorithms must be declared with a `DataPointEncoding` type, defined as follows, of either `VariableSize` or `FixedSize` which is chosen to best accommodate the compression.

```
enum {
    VariableSize = 0, // Encode data points with `DataPoint` structure
    FixedSize = 1     // Encode data points with `PaddedDataPoint` structure
}
DataPointEncoding;
```

The `VariableSize` encoding will serialize data using the `DataPoint` structure and the `FixedSize` encoding will serialize data using the `PaddedDataPoint` structure.


The compression algorithm encodings need to be known by and configured the publisher and subscriber; these encodings are used during *compression* and *decompression* stages to the proper data point encoding can be used. The `AlgorithmEncoding` structure, defined as follows, could be used to track these mappings:

```
struct {
    CompressionAlgorithm algorithm;
    DataPointEncoding encoding;
}
AlgorithmEncoding;

struct {
    uint16 count;
    AlgorithmEncoding[] items;
}
AlgorithmEncodings;
```

The session negotiation process specifies both the stateful compression algorithm to use as well as the stateless compression algorithm, when applicable.

The following compression algorithms should always be available for STTP implementations such that a minimal set of compression algorithms are always be available for a publisher/subscription connection session negotiation.

 TLS includes options to allow for payload level compression algorithms. When STTP implementations are configured with TLS security and an STTP defined compression option, the implementations should not

allow TLS compression options to also be enabled.

Any compression algorithms used by STTP may not increase the content length by more than 1,024 bytes. If the decompression function is used with a compressed data packet that would decompress to a length greater than 16,384 bytes, it must report a decompression failure error.

 The 2^{14} upper limit for decompressed buffers is the maximum payload size allowed by STTP.

No Compression

It is always possible for STTP to send data packets in their native binary format without any specified compression.

For the purposes of session negotiation the text name for selecting no compression is `NONE` and its version number is `0.0`.

Deflate Compression

Deflate is an industry-standard algorithm that is used for lossless compression and decompression. The Deflate compression algorithm is defined in RFC 1951 ^[19]. This algorithm was chosen as a safe default option for an always available compression option in STTP since implementations of the protocol are widely available on various operating systems and programming languages.

The Deflate algorithm is technically a stateful algorithm, however, it is defined for use within STTP in either stateful or stateless modes. In a stateless mode, the Deflate algorithm is simply applied to each data packet with its default initial state. The Deflate algorithm is the only default compression option that is specified for STTP stateless compression.

For the purposes of session negotiation the text name for the Deflate algorithm is `DEFLATE` and its version number is `1.0`.

Time-series Special Compression

The Time-series Special Compression algorithm (TSSC) is an algorithm specifically designed for STTP that is used to quickly compress streaming time-series data with very good compression ratios. The TSSC algorithm is defined in [Appendix E - TSSC Algorithm](#).

TSSC is a stateful compression algorithm that is specifically designed to work with STTP streaming data packets. As such it is only designed for use in STTP when the data channel functions are established with a reliable transport protocol, e.g., TCP.

For the purposes of session negotiation the text name for the Time-series Special Compression algorithm is `TSSC` and its version number is `1.0`.

Security

- Access control list (ACL) security is always on

Encrypted Communications

- Transport layer security (TLS) over TCP command channel
- UDP data channel traffic secured via AES keys exchanged over TCL command channel

Strong Identity Validation

- X.509 certificates
- Self-signed certificates

Publisher Initiated Security Considerations

How does publisher initiated connection, to cross security zones in desired direction, affect identity validation and TLS?

Access Control Lists

- Allow/deny for specific points (data point explicit)
- Allow/deny for group with specific points (group explicit)
- Allow/deny for filter expression (filter implicit)
- Allow/deny for group with filter expression (group implicit)

Expression based Access Control

- Expressions can be used to define filters and groups
- How do filters work against extensible metadata, missing columns?

Access Control Precedence

- (1) Data Point Explicit
- (2) Group Explicit
- (3) Filter Implicit
- (4) Group Implicit

References and Notes

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Bridge Energy Group				
Dominion Energy	♦		♦	EPG
Electric Power Group	♦	♦		
Electric Power Research Institute				
ERCOT			♦	
Grid Protection Alliance (Prime)	♦	♦		
ISO New England			♦	
MehtaTech		♦		
Oklahoma Gas & Electric	♦		♦	WSU
OSIsoft		♦		
Peak Reliability			♦	
PingThings		♦		
PJM Interconnection			♦	EPG
Southern California Edison			♦	
San Diego Gas & Electric	♦		♦	WSU
Schweitzer Engineering Laboratories	♦	♦		
Southern Company Services			♦	
Southwest Power Pool	♦		♦	WSU
Space-Time Insight		♦		
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Utilicast	♦	♦		
Tennessee Valley Authority	♦		♦	WSU
University of Southern California				
V&R Energy		♦		
Washington State University	♦	♦		
26	11	11	12	6

Specification Copyright Statement

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Major Version History

Version	Date	Notes
0.1	July 7, 2017	Initial draft for validation of use of markdown
0.0	June 15, 2017	Specification template

Appendix A - Initial Team Requirements



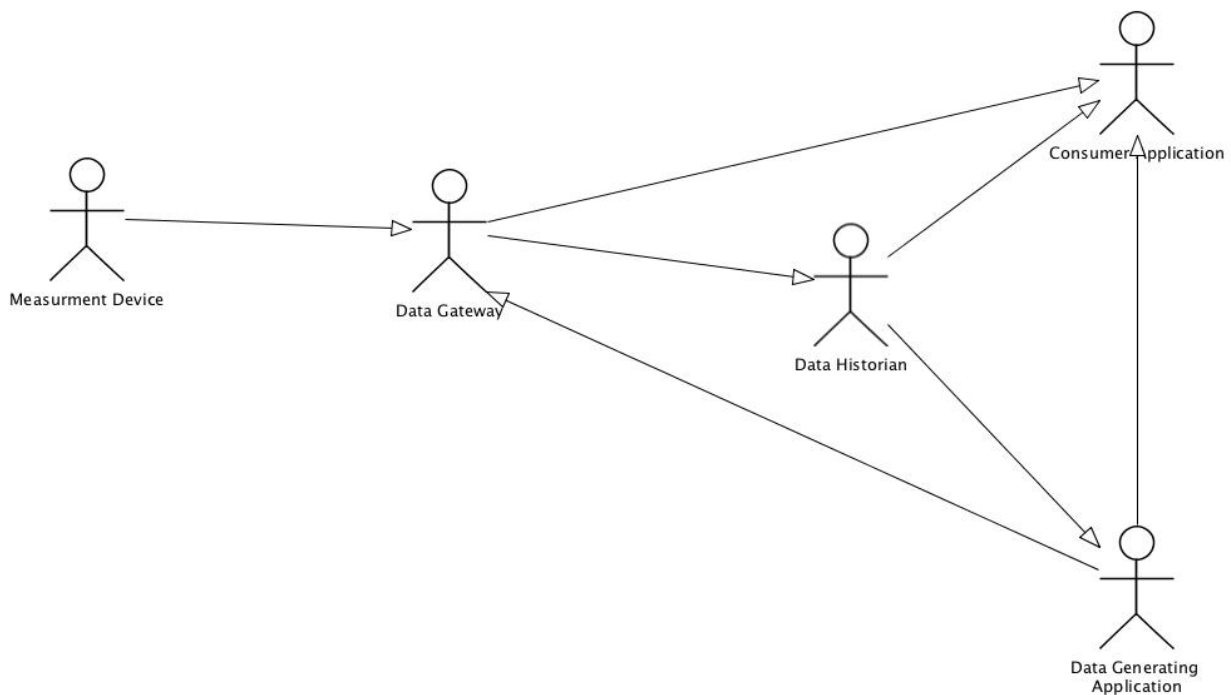
Overview:

Before setting out to create a definition of a new protocol, participation was solicited from a diverse set of stakeholders. Grid Protection Alliance (GPA) worked to assemble a group of users, academics, vendors and other stakeholders in order to vet the notion that a new protocol was actually needed and would provide value to our industries. Once the group convinced themselves that none of the known existing standards was a protocol that would solve the problems being encountered, with very large, high speed data sets, they worked together to document what this new protocol required. This appendix has been retained in the specification so that future users evaluating the use of the STTP protocol can see what drove the initial team in its creation of the protocol and associated APIs.

exist

STTP defines a measurement as an ID, Timestamp and values

At the highest level, STTP is expected to be used to manage data sourced from a measurement device through a data gateway/historian onto the using application. The following document is meant to show the likely interaction between the actors in this workflow:



Use Case Examples

First, an initial set of [use cases](#) were defined in order to document how stakeholders envisioned using this new STTP protocol. This is not meant to be an exhaustive list of all possible uses, but rather a sampling of the driving needs that led to the need to create a new protocol. These use cases were collected and organized by how the team envisioned them to be deployed in real world applications. This is not to limit implementation to one of these types, a system may implement a hybrid of two or more of these. However, each system will advertise the functions that it provides or services so that neighbor connections can know what is available.

While the protocol is meant to be flexible, there are a minimum set of features that must be provided for each use case implementation. In the below examples we will use an asterisk to designate those features that are desirable, but not required as part of the minimal implementation --- *optional features

Use Case #1 - Measurement Device

The most basic implementation of STTP will be in a measurement device. This could be a PMU, RTU or other device that is built to measure one or more values or conditions.

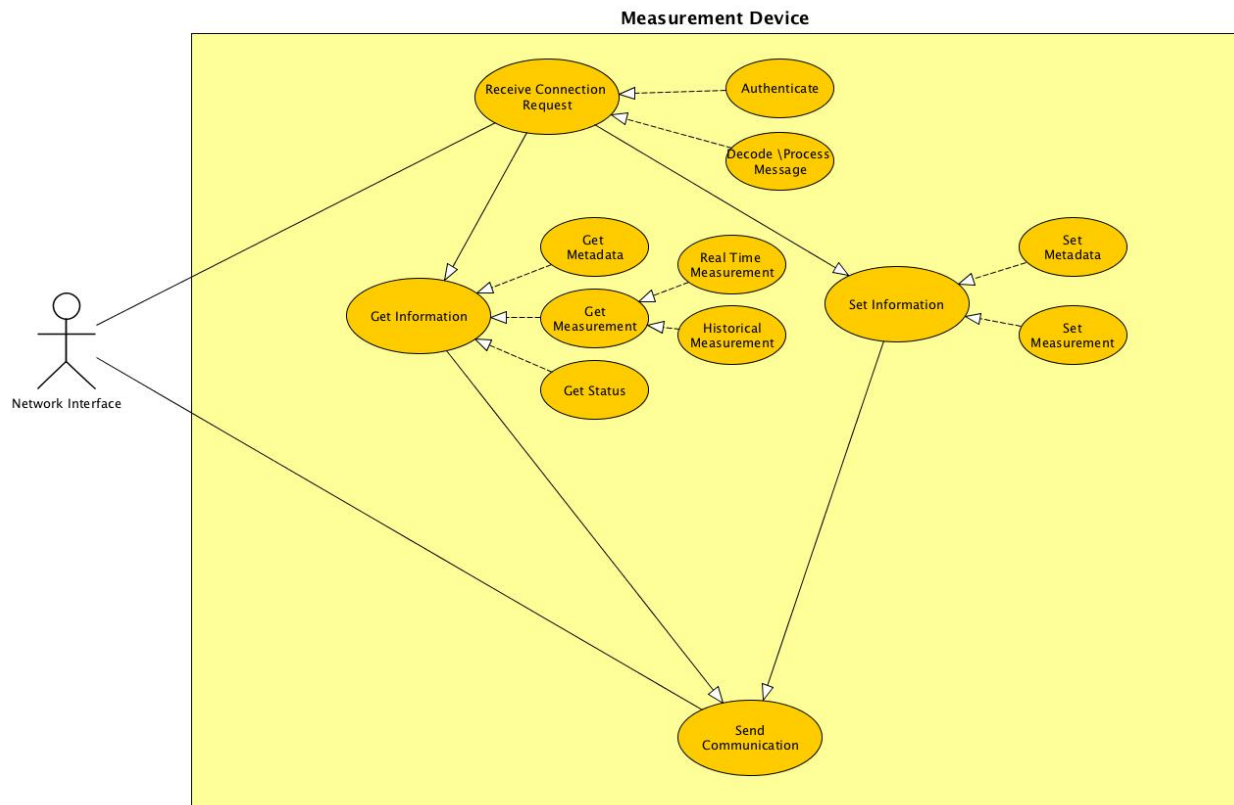
Use case definition statement:

As a measurement device with a Network Interface (NIC) connected to an IP based network, I would like to communicate with a Measurement Device using STTP, so that I may request data and metadata in a secured and efficient manner.

Features:

- Send Full Data Stream
- Send Basic Metadata
- Send Extended Metadata*
- Fulfill Data Stream Subscription Request*
- Fulfill Data Backfilling Request*
- Encryption*

- Data Compression*



Use Case #2 - Data Gateway

The next most likely implementation of STTP after measurement device is likely to be a computer to collect data from multiple measurement devices. With respect to STTP protocol these collection devices will be called Data Gateways. A data gateway allows downstream systems to request measurement streams from a number of different devices without having direct network access to the device themselves. The Data Gateway will forward a real time data stream for the requested measurements to authenticated and authorized requestors. In addition to real time data a Data Gateway will provide related metadata once requestors have been properly authenticated and authorized.

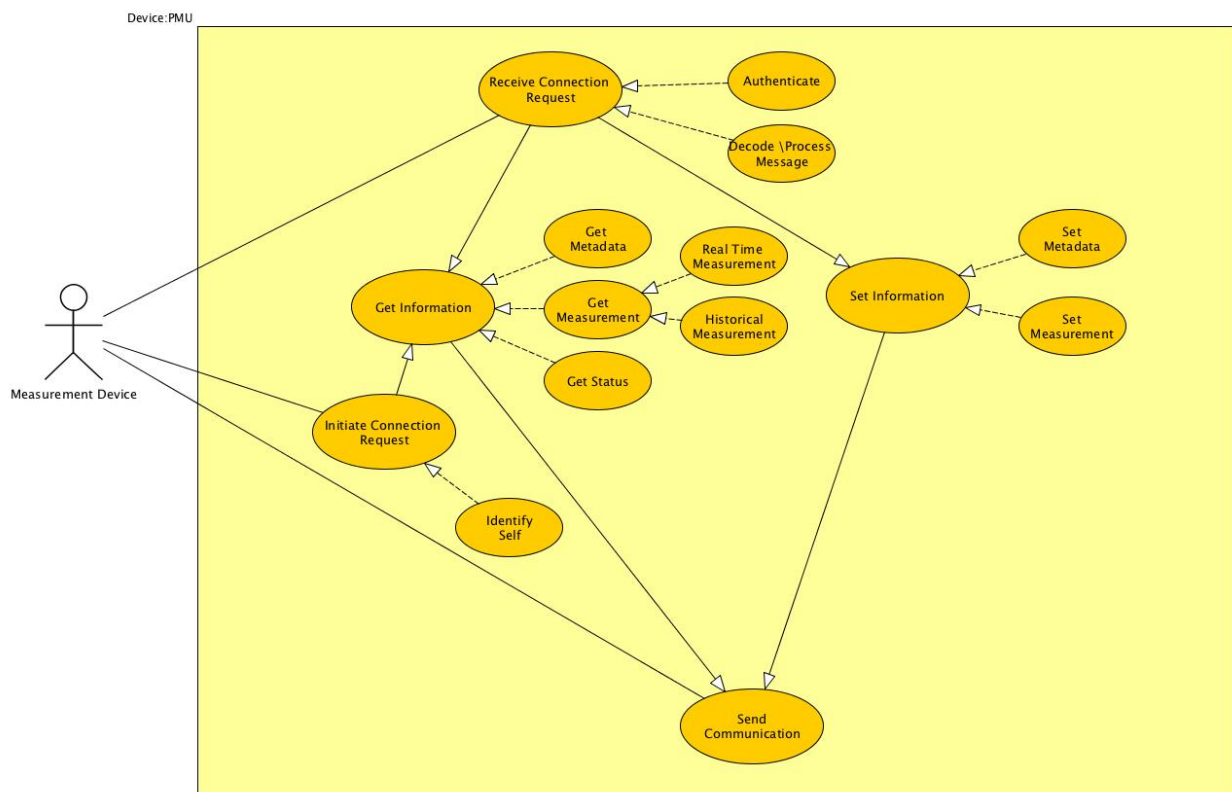
Use case definition statement:

As a data gateway with a Network Interface (NIC) connected to an IP based network, I would like collect as well as repackaging measurements received to those systems that are requesting real time feeds. using STTP, so that I may request data and metadata in a secured and efficient manner.

Features:

- Send Full Data Stream
- Send Basic Metadata
- Send Extended Metadata*
- Fulfill Data Stream Subscription Request*
- Fulfill Data Backfilling Request*
- Request Full Data Stream
- Request Basic Metadata
- Request Extended Metadata*

- Request Data Stream Subscription*
- Request Data Backfilling*
- Encryption*
- Data Compression*



Use Case #3 - Historian

The Historian supports many of the same features of a Dat Gateway. However its primary function is to store a historical record of both measurements as well as the associated metadata. The other major difference for a Historian compared to a gateway is that a historian may provide advanced filtering, summation, averaging or other advanced query mechanisms in addition to raw measurements.

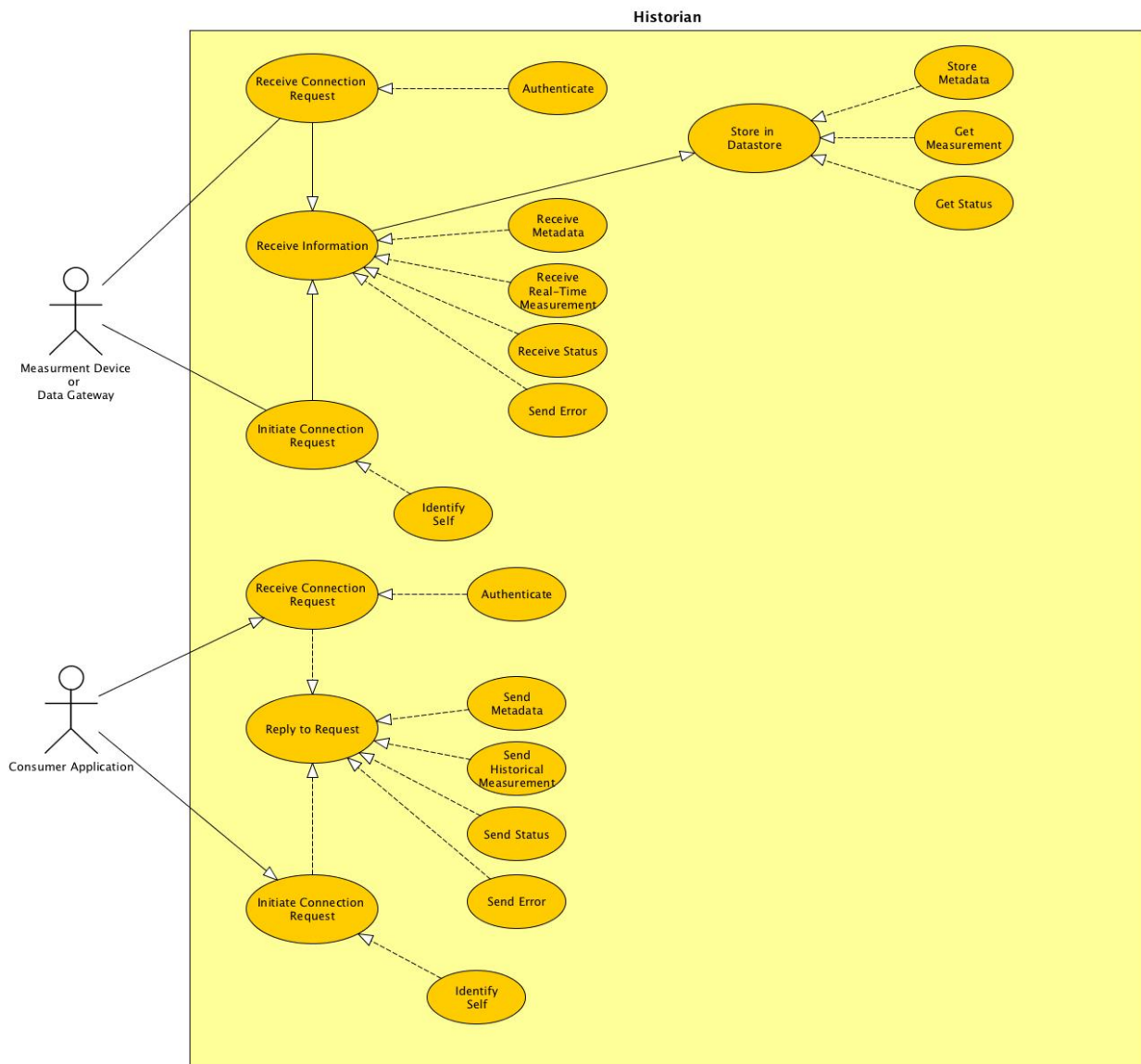
Use case definition statement:

As a designer of STTP I would like to be able to have an application that can collect real time data, store it for a long period of time and be able to sever the stored data back to authorized and authenticated users so that I may utilize in part or in full data measurement stream data after the fact.

Features:

- Send Full historical data stream
- Send filtered historical data stream
- Send Basic Metadata based on version or data
- Send Extended Metadata based on version or data
- Fulfill Data Stream Subscription Request for historical data
- Fulfill Data Backfilling Request*
- Request Full Data Stream
- Request filtered historical data stream

- Request Basic Metadata
- Request Extended Metadata*
- Request Data Stream Subscription*
- Request Data Backfilling*
- Encryption*
- Data Compression*
- Advanced Filters and Queries



Use Case #4 - Combination Gateway / Historian

as noted before the use cases are suggested implementations. It is expected that some systems will implement both the gateway as well as historian functions in a single system.

![[Gateway-Historian UML Image]

([https://raw.githubusercontent.com/sttp/Specification/master/Sections/Images/Use Case UML - Gateway-Historian.jpg](https://raw.githubusercontent.com/sttp/Specification/master/Sections/Images/Use%20Case%20UML%20-%20Gateway-Historian.jpg))

Use Case #4 - Consumer Application

Possibly the easiest to understand use case is the consumer application. A Consumer Application is any business (or IT) application that wishes to receive measurements via STTP. Good examples would include EMS or control

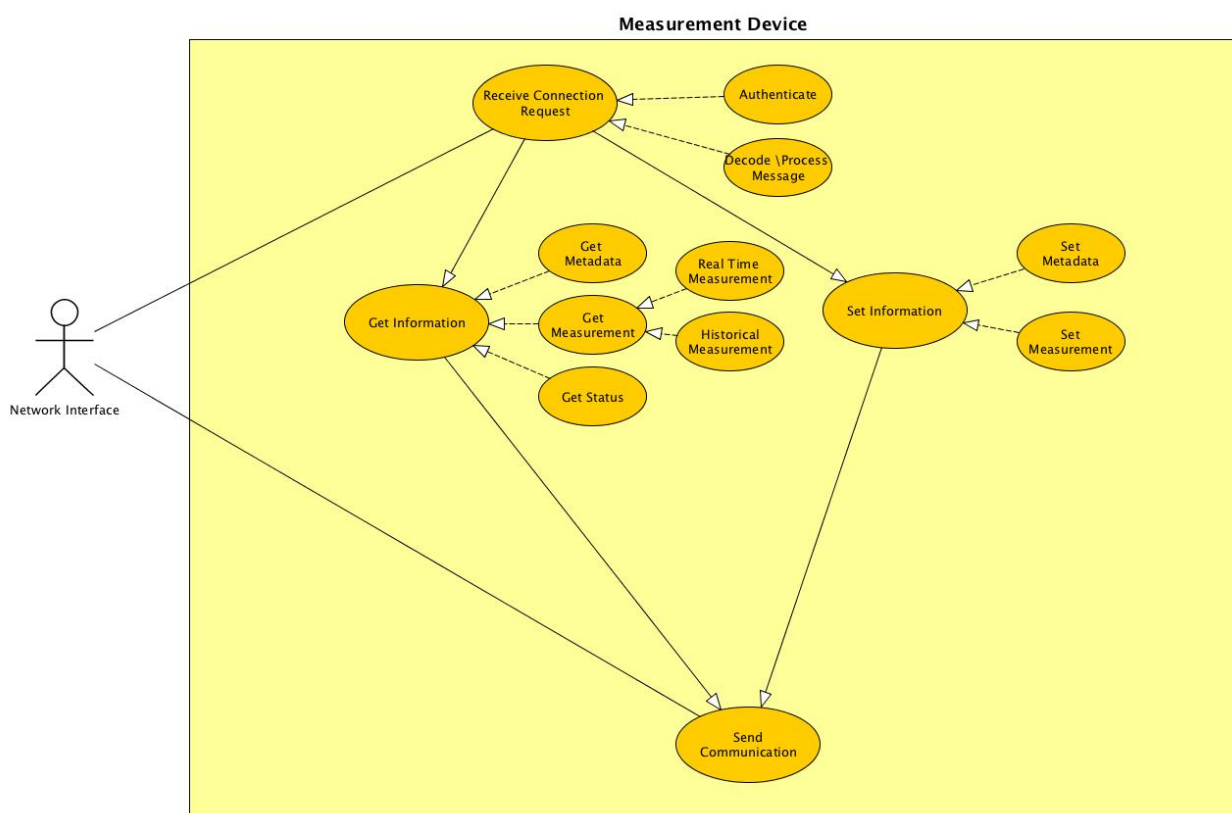
room visualization system. In this case an application would request measurement and metadata in order to use it in its own processing.

! [Consumer UML Image] (<https://raw.githubusercontent.com/sttp/Specification/master/Sections/Images/Use Case UML - Consumer.jpg>)

Use Case #4 - Data Generating Application

As we described above a measurement device will likely be the initial data set for STTP data. However it is expected that in addition to raw measurement devices there will be applications that create their own measurements. An example could be a state estimator that takes raw measurements and refines the data to give a cleaner picture.

For Purpose of use case, we can use the device documentation as they will provide essentially the same use cases. Just like regular devices they may also include gateway or historian functionality as well as the measurement action.



Functional Requirements

Functional requirements are the subset of total requirements that explains how an it system or one of its substations will work. Functional requirements represent the needs that drive the business utility of the any final solution, in this case the STTP protocol. Each functional requirement was defined to address a need that was not solved by existing. These functional requirements were defined by the initial stakeholders and drove the protocol design and creation.

The ASP solution will:

- Support a command channel or communications that are not measurements which will:
 - allow the subscribing gateway to start and stop the data stream.
 - exchange and optionally synchronize measurement point metadata information received from external

- trusted gateway unions to the local configuration source so that users can examine points that are available for subscription.
- enforce trusted gateway measurement point publication and subscription lists as defined in the configuration database. The system will drop data that it is not configured to receive.
 - provide the necessary mechanisms to negotiate QoS configuration with the receiving entity.
- allow for dynamically requesting data or metadata. It will not send all data all the time. Most often this requirement is met with the use of a publish-subscribe implementation where the receiver can request data elements and they are delivered by the source on event such as value change. **(Pub/Sub configurability)**
 - allow for the data to be requested (and sent) to multiple clients what may request the data elements in the same or different combinations.
 - allow the incoming connection to define the measurements that will be selectively streamed.**(Subscribed Data Stream)**
 - support the collection, maintenance and communication of data attributes or metadata. **(Metadata management)**
 - support tabular collection and sharing of metadata associated with measurements.
 - support metadata versioning, allowing a requester to ask for metadata as of a date or version id
 - support merging and update of metadata sets from multiple parties
 - support short descriptor for each data point.
 - the source system sending STTP data will be responsible for collection and sharing of metadata to authorized parties.
 - allow for the prioritization of data feeds. In addition to streaming data should take precedence over metadata, the streaming data should allow for the designation of a priority. Higher priority data flows should be given consideration in times of network congestion. **(Quality of Service)**
 - be capable of managing and streaming of very large sets. At time of authoring a very large set would be 1000 Phasor Measurement Units sending 10 streaming data points at a refresh rate of thirty times per second (.033ms per data for the same element) on a standard network (i.e 100mbps ethernet)
 - Incorporate access control for both data and metadata so that only authorized users are able to successfully receive information after a request. This security will be able to be set on a point by point basis (or element by element basis for metadata) **(Access Control)**
 - support measures to keep data from being viewed by non-authorized systems or staff. This will include the ability to implement standard, [not propitiatory to this protocol] encryption techniques. It will further provide the functions for management of the securing mechanisms. **(Confidentiality / Key management) (Enable best-practice security) (Reduced Risk of Non-Compliance)**
 - provide data channels encryption by default as well as require and the connection be authenticated. **(Encryption)**
 - Support reverse direction communication where security mechanisms have created a [unidirectional network](#). In this case a physical data diode or software based firewall may prevent a normal connection from the sender to the receiver (publisher to the subscriber) in this case the protocol will support a connection made from the higher security environment which may be the sender of the data to the receiver (or subscriber of the data). This effects only the setup of the connection. Once the connection is made normal functionality of publisher and subscriber are resumed. This data diode will then establish a connection with a lower security level and forward data to this client. The client will only be able to turn on/off the data stream, request metadata, and request a user

configurable amount of historical data that may be missing during a communications outage. These requests must be handled by the data diode with no modifications made to the established connection to the publisher.

- be easily deployed in configurations that allow for very high fault tolerance. This should include both network and client or server resiliency options. **(Deployment for high-availability) (Support Disaster recovery considerations)**
- allow backfilling missing data in the event of a communications outage. Receiving party would request and sending would respond with a data stream to fill in the missing data as defined by the receiver. **(Data Backfilling)**
- support advance compression methods. **(Data Stream Compression)**
- be capable of allowing the party that initiates a connection to be the sender, or publisher of data. **(Data Pushing)**
- minimize data losses over network connections that do not guarantee delivery (e.g. UDP)
- optimized for the performant delivery of individual data points (in contrast to 37.118 frame based optimization)
- capable of sending a subset or all of the data points to any connecting stream for very large collections of measurements.
- support exchange of metadata as well as the measurement data between any two or more participants in a conversation using the STTP protocol (no centralized registry required)
- support broadcast messaging and distribution of critical system alarms
- Each connection must operate independently of any other connection and isolate it to the extent possible.
- Support the following types of data requests:
 - **Subscription Delivery**
Per subscription delivery window - this subscription level setting would constrain data delivery to a provided timespan (in terms of UTC based start and stop time). This could either be a maximum (future) time constraint for real-time data or, where supported by publisher, a historical data request. Publisher will likely want to validate size of historical requests, or least throttle responses, for very large historical requests.
 - **sequence of values** - with respect to specified per value delivery settings (think buffer blocks)
 - **latest value** - command allows for non-streaming request/reply, such as, translation to DNP3
 - **historical values** - subject to availability of local archive / buffer with start and stop time- it has been requested many times that single value data recovery option will be available to accommodate for simple UDP loss, however this should be carefully considered since this basically makes UDP and TCP style protocol - if implemented, restored point should likely flow over TCP channel to reduce repeat recovery requests. Also, this should include detail in response message that recovery either succeeded or failed, where failure mode could include "data not available". To reduce noise, at connection time publisher should always let know subscriber its capabilities which might include "Support Historical Data Buffer" and perhaps depth of available data. That said there is true value in recovery of data gaps that occur due to loss of connectivity.

Non-Functional Requirements

In software requirements documentation, a non-functional requirement is a requirement that specifies criteria that specifies the operation of a system, rather than behaviors. Many often call non-functional requirements "quality attributes"

The ASP solution will:

- Support the transfer of very large number of streaming (1,000s to 10s of 1,000s simultaneously) data points streaming at high update rates (30-60 times per second **(Scalability)**)
- ensure data integrity end to end of any communication stream, for both streaming data and metadata **(Integrity)**
- Allow for future uses and data elements / attributes with minimal impact to the base protocol in order to allow for future improvements **(Extensibility)**
- be able to send as many data elements in a given time with the lowest latency possible for any given network configuration **(Performance and throughput [latency & bandwidth])**
- minimize bandwidth requirements on real time steaming of data using resend only on update as well as compression to Lower bandwidth requirements (e.g., over TCP)
- support solutions using protocol that are simple to installation and deploy and integrate with existing and new applications
- include APIs that support condition based Alarming and notifications based on defined events *(Alarming and notifications)*
- provide initial example API implementations in multiple languages, tested on multiple platforms to quickly utilize STTP protocol
- enforce a minimal set of metadata for any measurement type

To talk to Ritchie about(may not be true requirements or may just need additional clarification)

- Advance Queries - Must be able to handle more advance request/reply queries.
- Detect and expose communication issues
 - Points defined in metadata will have a clear ownership path
 - Industry specific metadata extensions will exist to support specific industry deployments

Appendix B - STTP API Reference

The STTP API describes a set of properties and methods for accessing an STTP server. Elements marked with the tag [Required] are required to be provided by all STTP server implementations.

? @StevenChisholm - please validate the accuracy / implementability of the following as compared to `TestImplementation` ...

Core

The Core class contains the basic elements of the API.

- `ConnectionString (handle : *handle): string`
[Required] returns the connection string of the current connection, or an empty string if no connection is established.
- `Connect(connectionString:string : String, SLL : Boolean, Certificate : X509CertificateClass) : *handle`
[Required] establishes a connection to the STTP server. SLL is True or false, if SLL is marked as TRUE then certificate must be provided. Upon successful connection it will provide a pointer to the handle used to describe this connection. The method will throw an exception if the connection cannot be established.
- `Disconnect(handle : *handle) : void`
[Required] terminates a connection. The communication path will be tore down and no traffic is guaranteed to be sent after a disconnect from either the server or the client.
- `ValidateConnection() : string`
> [Required] validates whether a connection has been successfully established. Returns the connection string, or an empty string if no connection is established.

Data

The Data class contains elements for querying and manipulating data points or the associated metadata.

Metadata Definition

Metadata is information that describes the measurements or the relationship between measurements. The party who is sending the data is allowed to modify the metadata. The ability to write data to the metadata repository is controlled by the security access. Any connection that does not have an SSL security certificate will default to sending party can modify and receiving party is read only. The methods defined in this section are only available if rights are granted to modify metadata repository.

- `AddTable (TableName : String) : Void`
[Required] allows for a new metadata definition table to be created. This method will raise an error if table is not created. (illegal tablename, name already exists, permissions do not allow modification)
- `RemoveTable (TableName : String) : Void`
[Required] removes a table from the metadata repository This method will raise an error if table is not created. (table name does not exists or permissions do not allow modification)

- **AddField (TableName : String, FieldName : String, DataType) : Void**
 [Required] allows for a new metadata definition field to be added to an existing table . This method will raise an error if table is not created. (table does not exist, illegal fieldname, name already exists, permissions do not allow modification)
- **RemoveField (TableName : String)**
 [Required] removes a field from the metadata repository This method will raise an error if table is not created. (Fieldname does not exist, table name does not exists or permissions do not allow modification)
- **AddRelationship (Table1, Table2, Field1, Field2, Relationship Type): Void**
 [Required] Used to define relationships between fields in different tables. Currently supports Foreign Key. Field 1 is a foreign key that is looked up in Field2. This method will raise an error is relationship is not able to be created
- **AddIndex (TableName : String, FieldName(s) : String, IndexType)**
 [Optional] removes a table from the metadata repository This method will raise an error if table is not created. (table name does not
- **SetVersion (Version : String)**
 > [Required] The provider of the metadata is expected to update the version number every time a change is made to metadata. This is not done automatically as the server side of the connection may be rebuilt due to a server issue and no metadata has changed.

Metadata Sharing

Once the Metadata is defined client can then request access to the information. The methods below describe how metadata is shared

- **GetMetaFormat(handle : *handle) : Integer**
 STTP supports multiple ways to store its metadata. Format is the format of the Metadata repository. This method is used for the client to request the format of the repository from the server. It can be one of the following integer values
 - Table Structure
 - XML Structure (future)
 - Object Model (future)
 - No Metadata Structure Defined

The underlying structure of the wire protocol metadata is Table Structure so in most cases table Structure will provide the best performance.
- **GetMetaVersion(handle : *handle) : Long Integer**
 Each time a change is made to the metadata the version is incremented. This method returns the ...
 - **GetMetaDataTableList(handle : *handle, Filter : String) : String[0...*]**
 Gets a list of the tables available for Metadata (tables may not have any rows, this method will return tables with zero rows) This method will return all tables plus the special table "Table_Relations. Filter syntax: FILTER TableName WHERE Expression [ORDER BY SortField]

- `GetMetaDataFieldList(handle : *handle, TableName : String) : String[0...*]`
Gets a list of the fields available for a table in the metadata repository. This method will return an array of strings that is a JSON formatted serialization of `FieldName`, `DataType`.
- `GetMetaData(handle : *handle, filter : String) : MetaData[0 .. *]`
[Required] gets `MetaData` for the current set of measurements. The metadata can be returned in a number of formats.
- `GetMetaDataDelta(handle : *handle, version : String) : MetaData[0 .. *]`
[Required] gets `MetaData` for the current set of measurements as a delta from the version that is provided. This method will raise an error if it is not able to fulfill the request.
- `GetMetaDataById(id:Guid) : MetaData`
[Required] gets `MetaData` for the measurement specified by `id`.
- `CacheMetaData(Status : Boolean, TTL : Int) : Status : Boolean`
[optional] [Required] Defines if the Metadata is to be cached or looked up on the server each time. If `status = True` then `TTL` is the Time to Live in seconds. It will check if cache is dirty at least every `TTL` seconds. If dirty it will repopulate (which may take longer than the `TTL` time in very large data sets with small `TTL`s. Status by default will be `False` meaning there is no cache.
- `IsCacheDirty() : Status : Boolean`
[optional]
- `RefreshCache() : Status : Boolean`
[optional] forces the cache to be updated. Used to update in-between `TTL`s as defined in `CacheMetaData` `TTL` or if `CacheMetaData` is set to `false`.
- `GetIDFromMetaData(MetaFilter : string) : MetaData[0 .. *]`
[optional] gets collection of data IDs that match the filter criteria.
** need to define what the nature of the filter is (SQL like?)
- `GetIdsWithUnprocessedData (handle : *handle, MetaFilter : string) : IDArray id:Guid[0 .. *]`
- `GetData (handle : *handle, Id : Guid)`
- `Subscribe(id:Guid) : Void`
[Required] initiates a subscription to the measurement specified by `id` at the native rate. Returns `True` if subscription is successful `False` otherwise.
- `Subscribe(id:Guid, rate:double, method:ResampleMethod) : Boolean`
[Required] initiates a subscription to the measurement specified by `id` at the delivery rate specified by `rate`. The underlying measurement shall be resampled using the method prescribed by `method`, which is a member of the `ResampleMethod` enumeration. This method will raise an error if it is unable to subscribe to the provided ID.
- `GetAvailableResampleMethodologies(handle : *handle, id:Guid[0 .. *]) : MetaData[0 .. *]`

[Required] gets the resampling rates available for each measurement.

💡 Basic resample methods must be mathematically defined in the standard and enumerated. If none of the available resample methods satisfy the subscriber's requirements, then the measurement should be subscribed at the native rate and resampled in the client application.

Publication Priority

1. As Soon as Possible
2. Normal Priority
3. As Able But Within a Timespan
4. As Able And Do Not Send After a TimeSpan
5. Throttled (Maximum of x-Bytes/Second) typically for historical data

Priority is set per measurements. By default a measurement is assigned Normal Priority (2). To change the priority use one of the following methods:

- `SetPublicationPriority(handle : *handle, id : Guid, Priority : Integer) : Void`

[Required] Sets the priority of the defined measurement to Priority

- `SetPublicationPriorityBulk(handle : *handle, filter, Priority : Integer) : Void`

[Optional] Sets the priority of the defined measurements for all measurements that are defined by the filter to Priority.

Security

The Security class contains elements for querying and manipulating the security features of a connection. All Roles and authentication is done through the use of a X509 certificate. If the certificate is not used, then there are no controls on what data is accessible or what metadata is able to be modified.

- `X509LatestAcceptedVersions (handle : *handle) : Version : String`

[Required] sends back a String with latest of the released X509 versions that are supported. Is it expected to utilize the latest version accepted by both the client and server.

- `X509AcceptedVersions (handle : *handle) : Versions_accepted : Tuple`

[Required] sends back a tuple with all versions of the 509 certificate standard that are accepted by the host

- `SecureConnection (handle : *handle, X509Certificate: X509CertificateClass)`

[Required] attempts to secure the communication of all future traffic on utilizing the handle. The certificate will be used to secure both data and command channels where they are separate sockets. The method will throw an exception if the connection cannot be established.

- `ModifyMetadataTableSecurity (handle : *handle, TableName : String, GroupName : String, Role : String) : Void`

> [Required] sets access for a defined group of users on a particular table. Users group is defined in X509 certificate. By default there all tables in the metadata repository are readable and editable by all users. If the group name had previously been assigned a role then the current call of this method will override previous setting assuming it completes successfully. Security is maintained at a table level. If some fields in a table need a different level of access then a second table should be created to hold the additional fields. Role can be

ReadOnly, ReadWrite, NotVisible. The method will throw an exception if the permission cannot be set.

Utility


The Utility class contains utility methods.

- `GetMaxFragmentSize() : Integer`

Returns the current max size of any message before it is fragmented (defaults to 1500 bytes)

- `SetMaxFragmentSize (MessageSize : Integer) : Void`

> Allows for setting of the message size. Should be equal to or smaller the largest size allowed by underlying network for a packet size. The method will throw an exception if the set is not applied.

 Links to language specific auto-generated XML code comment based API documentation would be useful.

more...

Appendix C - IEEE C37.118 Mapping

Today most all synchrophasor deployments include IEEE C37.118 in various parts of the infrastructure, this section describes how STTP will be mapped to and from IEEE C37.118 streams so that interoperability can be established with the existing protocol implementations and STTP, see [Figure 7](#).

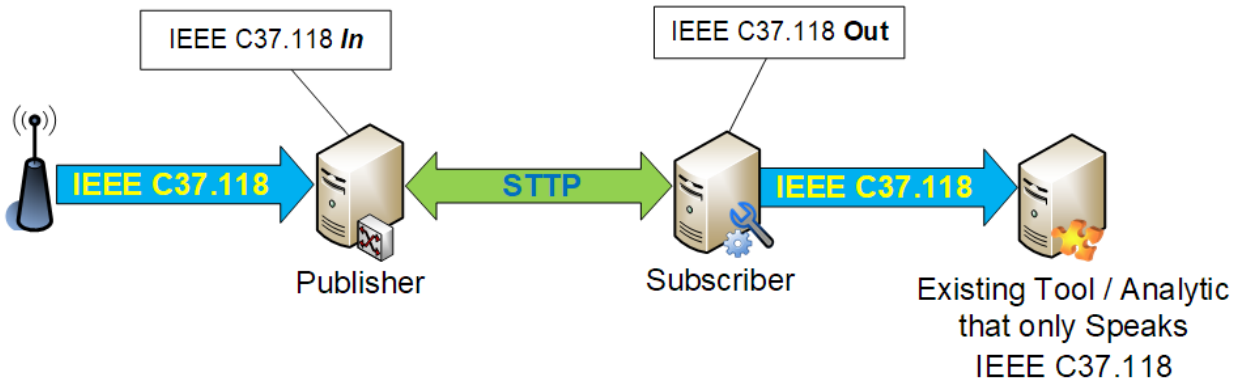


Figure 7

Appendix D - Other Protocol Evaluations

Various other standard protocols were evaluated for suitability as a starting point for STTP, most were quickly eliminated for one of the following reasons:

- Request / Reply (i.e., non-streaming) nature
- Insufficient specified limits on data throughput
- Restrictive payload formatting, e.g., inability to send binary data
- Forced transport specifications, e.g., HTTP

Other protocols that dealt with streaming data were found to not meet all the use case requirements that were desired for STTP. Suitability determinations for these protocols follows.

RFC 3350 - RTP: Transport Protocol for Real-Time Applications

At first blush, there seems to be much overlap in the requirements defined for the STTP protocol and those defined for RTP. In particular, its ability to reliably deliver real-time streaming data with several channels (e.g., audio and video) to a participant.

At a high-level, here are some the features of RTP:

- Used for applications transmitting real-time data, such as audio and video
- Designed to be independent of the underlying transport
- Services include payload type identification, sequence numbering, time-stamping and delivery monitoring
- Primarily designed to satisfy the needs of multi-participant multimedia conferences

RTP defines how to send, at a wire level, several related streams of data (i.e., content) for delivery to multiple participants simultaneously, i.e., all consumers receive the same data. However, since the desired use case for the STTP protocol can describe a different stream per consumer, i.e., where each consumer decides specifically what data they want, this multicast ability of RTP is not a feature that would be particularly useful. RTP also defines a fixed frame header timestamp that is used to synchronize several streams back together at the consumer level - such as lining up audio and video together for playback. The STTP use case, however, has a requirement to deliver a varying number of points each with its own timestamp, so the single header timestamp would not be useful “existing synchrophasor protocols also operate this way, i.e., with a single timestamp followed by payload measured at that time.

The RTP protocol also has stated caveats against multiplexing too many points:

5.2 Multiplexing RTP Sessions

For efficient protocol processing, the number of multiplexing points should be minimized, as described in the integrated layer processing design principle [10]. In RTP, multiplexing is provided by the destination transport address (network address and port number) which is different for each RTP session. For example, in a teleconference composed of audio and video media encoded separately, each medium SHOULD be carried in a separate RTP session with its own destination transport address.

Separate audio and video streams SHOULD NOT be carried in a single RTP session and demultiplexed based on the payload type or SSRC fields.

This indicates that the most appropriate use of this protocol would be to define each data point stream onto its own network address/port number - this would not be ideal as the total number of port numbers on a system is a fixed resource and the number of data points two STTP connections will want to exchange could range in the hundreds of thousands.

Perhaps the largest technical issue with RTP for the STTP use case is the fixed number of possible multiplexed points. The RTP protocol defines a SSRC per packet header field as well as multiple CCRC per packet header fields that allow you to identify up to 16 points (SSRC + 15 CCRC) in the same packet for a given timestamp. If you ignored the header timestamp and other stated issues, it might be possible to make RTP work for the streaming data portion of the STTP use case requirements if you took the 16 packet points, each with a fairly large header, and applied per-point identification in the data payload for each packet “ in this case the represented data could change packet-to-packet. However, doing this attempts to twist an existing protocol beyond its original design intentions to simply meet one portion of the needs of the current STTP use case simply for the sake of using an existing standard. This also does not solve the other STTP use case requirements, e.g., providing meta-data for the points being subscribed.

Regardless of the appropriateness of this standard to the desired use case, there is much that can be gleaned from this real-world production use protocol. In particular the dynamic ability to change encoding and frame-rates in response to changing network conditions should be noted as possible desired features of the STTP protocol.


Appendix E - TSSC Algorithm

The Time-series Special Compression algorithm (TSSC) was specifically designed for STTP and is used to quickly compress streaming time-series data packets with very good compression ratios.

TSSC is a stateful compression algorithm is intended to be used when the STTP data channel functions are established with a reliable transport protocol, e.g., TCP.

Fundamentally TSSC works by applying simple XOR based compression techniques and only sending bits of data that have changed since the last saved state. Although many compression algorithms use this technique for compression, TSSC achieves high compression ratios with the same techniques by taking advantage of the data point structure in use by STTP, i.e., that data points are based on a fixed set of elements, specifically an identifier, a timestamp, a set of quality flags and a value block. From a stateful compression perspective, each of these structural elements can be treated as four separate compression streams and handled differently based on their homogeneous nature and repeating patterns in the continuous data.

Contributing to the compression algorithm's success is that streaming data has a tendency to have some level of sequencing. For example one measured value will often follow another where a new measured value will have a timestamp that will have only slightly changed since the last measurement. Also, if the measurements are taken very rapidly, the difference in the actual measured value may also be small. By taking advantage of these non-entropic states for individual structure elements, compression is improved.

 Must be able to describe TSSC major functions verbally, at least by describing major code chunks. FYI, the following snippets were copied from GEP's TSSC implementation and will need to change based on architectural changes in STTP, e.g., multiple data types. Final code references should be in C language for a more universal example.

Code Words

Compression in TSSC happens per STTP data point element. Encoding compressed elements into a stream happens based a set of commands that describe the element targeted for compression and its compression state. The available code words are defined below.

```
const byte EndOfStream = 0;

const byte PointIDXOR4 = 1;
const byte PointIDXOR8 = 2;
const byte PointIDXOR12 = 3;
const byte PointIDXOR16 = 4;

const byte TimeDelta1Forward = 5;
const byte TimeDelta2Forward = 6;
const byte TimeDelta3Forward = 7;
const byte TimeDelta4Forward = 8;
const byte TimeDelta1Reverse = 9;
const byte TimeDelta2Reverse = 10;
const byte TimeDelta3Reverse = 11;
const byte TimeDelta4Reverse = 12;
const byte Timestamp2 = 13;
const byte TimeXOR7Bit = 14;

const byte Quality2 = 15;
const byte Quality7Bit32 = 16;

const byte Value1 = 17;
const byte Value2 = 18;
const byte Value3 = 19;
const byte ValueZero = 20;
const byte ValueXOR4 = 21;
const byte ValueXOR8 = 22;
const byte ValueXOR12 = 23;
const byte ValueXOR16 = 24;
const byte ValueXOR20 = 25;
const byte ValueXOR24 = 26;
const byte ValueXOR28 = 27;
const byte ValueXOR32 = 28;
```

Encoding

The following defines a class that represents the encoder for each STTP data point.

 Break down functions into details and describe

```

class TsscEncoder
{
    const uint Bits28 = 0xFFFFFFFFu;
    const uint Bits24 = 0xFFFFFFFFu;
    const uint Bits20 = 0xFFFFFu;
    const uint Bits16 = 0xFFFFu;
    const uint Bits12 = 0xFFFu;
    const uint Bits8 = 0xFFu;
    const uint Bits4 = 0xFu;
    const uint Bits0 = 0x0u;

    private byte[] m_data;
    private int m_position;
    private int m_lastPosition;

    private long m_prevTimestamp1;
    private long m_prevTimestamp2;

    private long m_prevTimeDelta1;
    private long m_prevTimeDelta2;
    private long m_prevTimeDelta3;
    private long m_prevTimeDelta4;

    private TsscPointMetadata m_lastPoint;
    private IndexedArray<TsscPointMetadata> m_points;

    public void Reset() {}

    public void SetBuffer(byte[] data, int startingPosition, int length) {}

    public int FinishBlock() {}

    public unsafe bool TryAddMeasurement(ushort id, long timestamp, uint quality, float value) {
    }

    /* CODE TRUNCATED */

```

Decoding

The following defines a class that represents the encoder for each STTP data point.

🚧 Break down functions into details and describe

```

class TsscDecoder
{
    private byte[] m_data;
    private int m_position;
    private int m_lastPosition;

    private long m_prevTimestamp1;
    private long m_prevTimestamp2;

    private long m_prevTimeDelta1;
    private long m_prevTimeDelta2;
    private long m_prevTimeDelta3;
    private long m_prevTimeDelta4;

    private TsscPointMetadata m_lastPoint;
    private IndexedArray<TsscPointMetadata> m_points;

    public void Reset() {}

    public void SetBuffer(byte[] data, int startingPosition, int length) {}

    public unsafe bool TryGetMeasurement(out ushort id, out long timestamp, out uint quality, out
    private void DecodePointID(int code, TsscPointMetadata lastPoint) {}

    private long DecodeTimestamp(int code) {}

    private uint DecodeQuality(int code, TsscPointMetadata nextPoint) {}
}

/* CODE TRUNCATED */

```

Data Point Metadata

The following defines a class that represents the metadata stored for each STTP data point.

🚧 Break down functions into details and describe

```

class TsscPointMetadata
{
    public ushort PrevNextPointId1;

    public uint PrevQuality1;
    public uint PrevQuality2;
    public uint PrevValue1;
    public uint PrevValue2;
    public uint PrevValue3;

    private readonly byte[] m_commandStats;
    private int m_commandsSentSinceLastChange = 0;

    private byte m_mode;
    private byte m_mode21;
    private byte m_mode31;
    private byte m_mode301;
    private byte m_mode41;
    private byte m_mode401;
    private byte m_mode4001;

    private int m_startupMode = 0;
    private readonly Action<int, int> m_writeBits;
    private readonly Func<int> m_readBit;
    private readonly Func<int> m_readBits5;

    public TsscPointMetadata(Action<int, int> writeBits, Func<int> readBit, Func<int> readBits5)

    public void WriteCode(int code) {}

    public int ReadCode() {}

    private void UpdatedCodeStatistics(int code) {}

    private void AdaptCommands() {}
}

/* CODE TRUNCATED */

```

Appendix F - STTP Templates

Overview

The base STTP protocol can be used for any type of time series data. However, if every implementation of STTP is unique then sharing metadata in an automated fashion will be unique for each implementation. In order to assist in standardization of the grouping of data and streamlining the structure of the metadata templates are defined.

A template is a schema that defines how the base metadata will be organized and how the data structure should be sent. Since the STTP was initially designed to support synchrophasor data included below is a conversations about the elements of the PMU template

Here are some examples of metadata suitable for the electric power industry.

DataPoint Table

A publisher might try the following DataPoint Table for the power industry.

Attribute Name	Attribute Value Type	Description
PointID	Guid	The GUID associated with the data point.
PointTag	String	A string based unique identifier.
Description	String	A description for this measurement
ProducerTableName	String	The name of the table within which the record for the resource that produced this data point resides.
ProducerTableID	Guid	The primary key for the record within the Producer Table.
SignalReference	String	A string based unique identifier
SignalTypeID	Integer	A code describing the signal type
Adder	Float	An adjustment factor
Multiplier	Float	An adjustment factor
Signal Type	String	Fixed set of signal types. I.E.: (STAT FREQ DFREQ PM PA PR PI ANALOG DIGITAL CALC)
Phase Designation	String	The phase this field is computed from. Ex: A,B,C,0,+,-
Engineering Units	String	The base units of this field. (Ex: Volts, Amps, Watts)
Engineering Scale	Float	The scaling factor of these units (Ex: 1, 1000, 1000,000)
Channel Name	String	C37.118 Channel Name. For Digital types, an array of 16 elements are permitted. Array length shall be zero if this is not a C37.118 - derived data point.
PositionIndex	Integer	C37.118 position index in a PMU frame. Zero for non-C37.118 data points.

PMU Table (a Resource Table example)

	Attribute	
--	-----------	--

Attribute Name	Value Type	Description
ResourceID	Guid	The GUID associated with the resource.
Acronym	String	A name of the device.
Name	String	A friendly name of the device
SubstationTableName	String	The name of the table within which the record for the substation where this PMU resides.
SubstationTableID	Guid	The primary key for the record within the substation table.
CompanyTableName	String	The name of the table within which the record for the company that owns this PMU.
CompanyTableID	Guid	The primary key for the record within the company table.
Protocol	String	The protocol the device is communicating with
FrameRate	String	The sample rate
FNOM	String	C37.118 Nominal Frequency
IDCODE	String	C37.118 ID Code
STN	String	C37.118 Station Name
Nominal Voltage	Float	The factor required to convert this voltage to a per unit base.
CT Ratio	Float	The ratio of a connected CT
Rated MVA	Float	The nominal rating of this device
Vendor	String	The vendor of this device
Model	String	The model number of this device
Equipment Type	String	The type of equipment this device is monitoring (Ex: Line, Transformer)
Serial Number	String	Serial numbers or other identifying information about this equipment)
In Service Date	Date	The date this device was put in service
Out Service Date	Date	The date this device was removed from service

Substation Table (a Resource Table example)

Attribute Name	Attribute Value Type	Description
ResourceID	Guid	The GUID associated with the resource.
Name	String	A friendly name of the substation.
Latitude	Float	The latitude of the substation.
Longitude	Float	The location of the substation.
TimeZone	String	The time zone for the substation.

Phasor Table (a CDSM Table example)

The existence of this CDSM Table presumes the existence of a 'built-in' CDSM called 'Phasor'. For this example, assume that the Phasor CDSM is comprised of two fields: Magnitude (float) and Angle (float).

Attribute Name	Attribute Value Type	Description
CDSMID	Guid	The GUID associated with an entry in the Phasor CDSM.
CDSMTag	String	A string based unique identifier for the Phasor.
Description	String	A description for this phasor, e.g. 'Smith Substation North Bus Voltage'.
IsCurrent	Bit	Set if this is a current phasor.
VoltAssociation	Guid	The ID of the voltage phasor used to compute power. Ignore if IsCurrent is reset.
AlternateVolt	Guid	An alternate voltage phasor, used when the primary voltage is unavailable. Ignore if IsCurrent is reset.
LineTableName	String	The name of the table within which the record for the line associated with this current phasor resides. Ignore if IsCurrent is reset.
LineTableID	Guid	The primary key for the record within the line table. Ignore if IsCurrent is reset.

VIPair Table (a CDSM example)

The existence of this CDSM Table presumes the existence of a CDSM, 'built-in' or 'user-defined', called 'VIPair'. For this example, assume that the VIPair CDSM is comprised of two fields: Voltage (Phasor CDSM) and Current (Phasor CDSM).

Attribute Name	Attribute Value Type	Description
CDSMID	Guid	The GUID associated with an entry in the VIPair CDSM.
CDSMTag	String	A string based unique identifier for the VIPair.
Description	String	A description for this VIPair, e.g. 'Smith-Jones Line'.

Data Point Time Quality Flags - Move to appendix

Data points can also include a `TimeQualityFlags` structure in the serialized state data, defined below, that describes both the timestamp quality, defined with the `TimeQuality` enumeration value, as well as an indication of if a timestamp was not measured with an accurate time source.

The time quality detail is included for devices that have access to a GPS or UTC time synchronization source, e.g., from an IRIG timecode signal. For timestamps that are acquired without an accurate time source, e.g., using the local system clock, the `TimeQuality` value should be set to `Locked` and the `TimeQualityFlags.NoAccurateTimeSource` should be set.

```
enum {
    Locked = 0x0,                // Clock locked, Normal operation
    Failure = 0xF,               // Clock fault, time not reliable
    Unlocked10Seconds = 0xB,     // Clock unlocked, time within 10^1s
    Unlocked1Second = 0xA,       // Clock unlocked, time within 10^0s
    UnlockedPoint1Seconds = 0x9, // Clock unlocked, time within 10^-1s
    UnlockedPoint01Seconds = 0x8, // Clock unlocked, time within 10^-2s
    UnlockedPoint001Seconds = 0x7, // Clock unlocked, time within 10^-3s
    UnlockedPoint0001Seconds = 0x6, // Clock unlocked, time within 10^-4s
    UnlockedPoint00001Seconds = 0x5, // Clock unlocked, time within 10^-5s
    UnlockedPoint000001Seconds = 0x4, // Clock unlocked, time within 10^-6s
    UnlockedPoint0000001Seconds = 0x3, // Clock unlocked, time within 10^-7s
    UnlockedPoint00000001Seconds = 0x2, // Clock unlocked, time within 10^-8s
    UnlockedPoint000000001Seconds = 0x1 // Clock unlocked, time within 10^-9s
}
TimeQuality; // 4-bits, 1-nibble

enum {
    None = 0,
    TimeQualityMask = 0xF,          // Mask for TimeQuality
    NoAccurateTimeSource = 1 << 7 // Accurate time source is unavailable
}
TimeQualityFlags; // sizeof(uint8), 1-byte
```

🚧 The remaining available bits in the `TimeQualityFlags` enumeration could be made to directly map to IEEE C37.118 leap-second flags. Existing IEEE text could then be used to describe the function of these bits if deemed useful:

```
LeapsecondPending = 1 << 4, // Set before a leap second occurs and then cleared after
LeapsecondOccurred = 1 << 5, // Set in the first second after the leap second occurs and remain
LeapsecondDirection = 1 << 6, // Clear for add, set for delete
```

Data Point Data Quality Flags - Move to appendix

A set of data quality flags are defined for STTP data point values in the `DataQualityFlags` enumeration, defined as follows:

```
enum {
    Normal = 0,                // Defines normal state
    BadTime = 1 << 0,          // Defines bad time state when set
    BadValue = 1 << 1,         // Defines bad value state when set
    UnreasonableValue = 1 << 2, // Defines unreasonable value state when set
    CalculatedValue = 1 << 3,   // Defines calculated value state when set
    MissingValue = 1 << 4,      // Defines missing value when set
    ReservedFlag = 1 << 5,       // Reserved flag
    UserDefinedFlag1 = 1 << 6,   // User defined flag 1
    UserDefinedFlag2 = 1 << 7    // User defined flag 2
}
DataQualityFlags; // sizeof(uint8), 1-byte
```

📘 These quality flags are intentionally simple to accommodate a very wide set of use cases and still provide some indication of data point value quality. More complex data qualities can exist as new data points.