                 GigaBeam High-Speed Radio Link Encryption

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Abstract

   This document describes the encryption and key management used by
   GigaBeam as part of the WiFiber(tm) family of radio link products.
   The security solution is documented in the hope that other wireless
   product development efforts will include comparable capabilities.

1. Introduction

   The GigaBeam WiFiber(tm) product family provides a high-speed point-
   to-point radio link. Data rates exceed 1 gigabit/second at a
   distance of about a mile. The transmission beam width is less than
   one degree, which means that attempts to intercept the signal are
   most successful when the attacker is either between the transmitter
   and receiver or the attacker is directly behind the receiver. Since
   interception is possible, some customers require confidentiality and
   integrity protection for the data on the radio link. This document
   describes the security solution designed and deployed by GigaBeam to
   provide these security services.

   The GigaBeam security solution employs:

      o AES-GCM [GCM] with a custom security protocol specified in this
         document to provide confidentiality and integrity protection of
         subscriber traffic on the radio link;

      o AES-CBC [CBC] and HMAC-SHA-1 [HMAC] with IPsec ESP [ESP] to
         provide confidentiality and integrity protection of management
         traffic between the radio control modules;

      o AES-CBC [CBC] and HMAC-SHA-1 [HMAC] with the IKE protocol [IKE]
         to provide confidentiality and integrity protection of key
         management traffic between the radio control modules; and

      o OAKLEY key agreement [OAKLEY] and RSA digital signatures
         [PKCS1] are used with IKE to establish keying material and to
         provide authentication.

   AES-GCM is used with the custom security protocol in a manner that is
   very similar to its use in ESP [ESP-GCM].

2. GigaBeam High-Speed Radio Link Overview

   The GigaBeam high-speed radio link appears to be a fiber interface
   between two network devices. Figure 1 illustrates the connection of
   two devices that normally communicate using Gigabit Ethernet over a
   fiber optic cable.

```
    +---------+     +----------+      +----------+     +---------+
    |         |     |      +----/     |          |     |         |
    | Network |     | GigaBeam |   /  | GigaBeam |     | Network |
    | Device  +=====+  Radio   |  /---- +  Radio   +=====+ Device  |
    |         |     |          |      |          |     |         |
    +---------+  ^  +----------+   ^  +----------+  ^  +---------+
                 |                 |                |
                 |                 |                |
       Gigabit Ethernet           |       Gigabit Ethernet
                      GigaBeam Radio Link
```
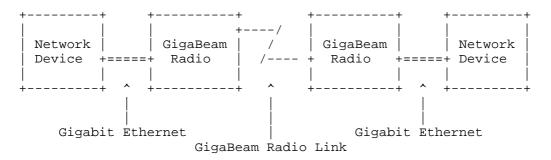
                 Figure 1. GigaBeam Radio Link Example.

   Gigabit Ethernet traffic is encoded in 8B/10B format. The GigaBeam
   Radio Control Module (RCM) removes this coding to recover the 8-bit
   characters plus an indication of whether the character is a control
   code. The radio link frame is constructed from 224 10-bit input
   words, and a 4-way interleaved (56,50,10) Reed-Solomon Forward Error
   Correction (FEC) block is employed. Conversion of the Gigabit
   Ethernet data from 8B/10B format creates 224 bits of additional
   capacity in each frame, and another 196 bits is gained by recoding
   the 9-bit data using 64B/65B block codes. This additional 420 bits
   of capacity is used for the framing overhead required for FEC and
   link control.

2.1. GigaBeam Radio Link Frame Format

   The GigaBeam radio link frame fields are summarized in Figure 2,
   which also provides the length of each field in bits.

        Field   Length   Description
        -----   ------   -----------
        SYNC   11   Frame Synchronization Pattern ('10110111000'b)
        KEYSEL   1   Indicates which AES key was used for this frame
        PN   40   AES-GCM Packet Number
        FLAGS   28   Control bits, one bit for each 64B/65B data block
        DCC   8   Data Communications Channel
        DATA   1792   Data (28 encrypted 64B/65B code blocks)
        TAG   96   Authentication Tag
        SPARE   24   Reserved for alternative FEC algorithms
        CHECK   240   Reed-Solomon Check Words for 4 10-bit
                          symbol (56,50) code

                Figure 2. GigaBeam Radio Link Frame Structure.

   Each of the fields in the GigaBeam 2240-bit radio link frame is
   described below.

        SYNC   Synchronization field, an 11-bit Barker code. Always set
                  to '10110111000'b.

        KEYSEL   Key Selector -- select the appropriate key register for
                  this frame. Two key registers are maintained to allow
                  seamless rollover between encryption keys.

        PN   Packet Number -- needed by AES-GCM; it carries the unique
                  counter value for this frame. The value is incremented
                  for each frame.

        FLAGS   Control bits, one for each 64B/65B data block carried in
                  the DATA field. If the bit is set, then the
                  corresponding 64B/65B block in the DATA field contains a
                  control code. This field is integrity protected by AES-
                  GCM.

        DCC   Data Communications Channel -- each frame carries one
                  octet of the point-to-point data communications channel
                  between the two radio control modules. See Section 2.2
                  for more information on the DCC.

        DATA   Subscriber data carried as 28 64B/65B code blocks. This
                  field is encrypted and integrity protected by AES-GCM.

       TAG   The authentication tag generated by AES-GCM, truncated to
                 96 bits.

       SPARE   24 bits, set to zero.

       CHECK   Forward error correction check value -- 24 check symbols
                 are generated by a 4-way interleaved Reed-Solomon
                 (56,50,10) algorithm. FEC is always active, but
                 correction can be selectively enabled. For each frame,
                 FEC processing also returns the number of bit errors, the
                 number of symbols in error, and whether the FEC
                 processing failed for the frame. This information allows
                 an estimation of the bit error rate for the link.

2.2. Data Communications Channel

   The Data Communications Channel (DCC) field reserves eight bits in
   each 2240-bit radio link frame for use in constructing a dedicated
   point-to-point link between the two RCMs. The DCC content is
   connected to a Universal Asynchronous Receiver/Transmitter (UART)
   controller that processes the DCC bit stream to provide an
   asynchronous serial channel that is visible to the RCM operating
   system. The Point-to-Point Protocol (PPP) [PPP] is used on the
   serial channel to create a simple two-node Internet Protocol (IP)
   network. Each IP datagram is spread over a large number of radio
   link frames. This two-node IP network carries management protocols
   between the GigaBeam RCMs.

   IKE [IKE] runs on this two-node IP network to manage all
   cryptographic keying material. IPsec ESP [ESP] is used in the usual
   fashion to protect all non-IKE traffic on the data control channel.
   IPsec ESP employs AES-CBC as described in [ESP-CBC] and HMAC-SHA-1 as
   described in [ESP-HMAC].

3. Radio Link Processing

   The fiber interface constantly provides a stream of data encoded in
   8B/10B format. A radio link frame is constructed from 224 10-bit
   input words. Conversion of the data from 8B/10B format creates 224
   bits of additional capacity in each frame, and then recoding using
   64B/65B block codes creates another 196 bits of additional capacity.
   After encryption, the 64B/65B blocks are carried in the DATA field,
   and the control code indicator bits are carried in the FLAGS field.
   The additional capacity is used for the framing overhead.

Processing proceeds as follows:

o   encryption and integrity protection as described in Section 3.1;

o   forward error correction (FEC) processing as described in Section
    3.2;

o   scrambling as described in Section 3.3; and

o   differential encoding as described in Section 3.4.

3.1. Encryption and Integrity Protection

   The GigaBeam RCM contains two key registers. The single-bit KEYSEL
   field indicates which of the two registers was used for the frame.

   AES-GCM [GCM] employs counter mode for encryption. Therefore, a
   unique value for each frame is needed to construct the counter. The
   counter includes a 32-bit salt value provided by IKE and a 40-bit
   packet number from the PN field in the radio link frame. The same
   counter value must not be used for more than one frame encrypted with
   the same key. The 128-bit counter block is constructed as shown in
   Figure 3. The first 96 bits of the AES counter block are called the
   Nonce in the AES-GCM algorithm description. Note that AES-GCM uses
   BLOCK values of zero and one for its own use. The values beginning
   with two are used for encrypting the radio link frame payload.

        Field   Length   Description
        -----   ------   -----------
        SALT   32   Salt value generated during the IKE exchange
        MBZ1   24   These bits must be zero
        PN   40   AES-GCM Packet Number carried in PN field
        MBZ2   28   These bits must be zero
        BLOCK   4   Block counter used in AES-GCM

                Figure 3. AES Counter Block Construction.

   AES-GCM is used to protect the FLAGS and DATA fields. The FLAGS
   field is treated as authenticated header data, and it is integrity
   protected, but it is not encrypted. The DATA field is encrypted and
   authenticated. The TAG field contains the authentication tag
   generated by AES-GCM, truncated to 96 bits.

   Reception processing performs decryption and integrity checking. If
   the integrity checks fail, to maintain a continuous stream of
   traffic, the frame is replaced with K30.7 control characters. These

control characters are normally used to mark errors in the data
stream. Without encryption and integrity checking, these control
characters usually indicate 8B/10B running disparity or code errors.

3.2. Forward Error Correction (FEC)

The 224 10-bit data symbols that make up each radio link frame are
grouped into 4 subframes each consisting of 56 symbols. The
subframes are formed by symbol interleaving. A Reed-Solomon Code,
RS(56,50), designed for 10-bit symbols is applied to each subframe.

This Reed Solomon Code detects 6 errors and corrects 3 errors within
each subframe. The FEC function is always active; however, it is
possible to disable correction of the received data to support
debugging.

3.3. Scrambler

The scrambler ensures that long series of one bits and long series of
zero bits do not occur. When encryption is enabled, long series of
common bit values is very unlikely; however, during the initial IKE
exchange, the radio link frame payload is all zero bits.

The scrambling polynomial is $(1 + x^{14} + x^{15})$. All words of a frame
except the SYNC pattern are scrambled prior to transmission using
this linear feedback shift register (LFSR). The LFSR is initialized
to all ones at the start of each frame, prior to the first processed
bit. Each processed input bit is added modulo 2 (i.e., an XOR) to
the output of the x15 tap to form the output bit.

On reception, an identical process is performed after frame
synchronization and prior to subsequent processing to recover the
original bit pattern.

3.4. Differential Encoding

The data stream is differentially encoded to avoid symbol ambiguity
at the receiver. Since the demodulator could produce true or
inverted data depending on the details of the radio frequency (RF)
and intermediate frequency (IF) processing chains, differential
encoding is used to ensure proper reception of the intended bit
value. A zero bit is encoded as no change from the previous output
bit, and a one bit is encoded as a change from the previous output
bit. Thus, an output bit is the result of XORing the unencoded bit
with the previously transmitted encoded bit.

On reception, a complementary operation will be performed to produce
the decoded datastream. The bitstream is formed by XORing the
received encoded bit and the previously received encoded bit.

4. Key Management

The Internet Key Exchange (IKE) is used for key management [IKE].
IKE has two phases. In Phase 1, two Internet Security Association
and Key Management Protocol (ISAKMP) peers establish a secure,
authenticated channel with which to communicate. This is called the
ISAKMP Security Association (SA). In the GigaBeam environment, the
Phase 1 exchange is IKE Aggressive Mode with signatures and
certificates. The RSA signature algorithm is used.

Phase 2 negotiates the Security Associations for the GigaBeam custom
security protocol that protects subscriber traffic and IPsec ESP that
protects management traffic between the GigaBeam RCMs. In the
GigaBeam environment, the Phase 2 exchange is IKE Quick Mode, without
perfect forward secrecy (PFS). The information exchanged along with
Quick Mode is protected by the ISAKMP SA. That is, all payloads
except the ISAKMP header are encrypted. A detailed description of
Quick Mode can be found in Section 5.5 of [IKE].

When the Security Association is no longer needed, the ISAKMP Delete
Payload is used to tell the peer GigaBeam device that it is being
discarded.

4.1. Certificates

Each GigaBeam device generates its own public/private key pair. This
generation is performed at the factory, and the public key is
certified by a Certification Authority (CA) in the factory. The
certificate includes a name of the following format:

C=US O=GigaBeam Corporation OU=GigaBeam WiFiber(tm)
SerialNumber=<device-model-identifier>/<device-serial-number>

The ISAKMP Certificate Payload is used to transport certificates, and
in the GigaBeam environment, the "X.509 Certificate - Signature"
certificate encoding type (indicated by a value of 4) is always used.

GigaBeam devices are always installed in pairs. At installation
time, each one is configured with the device model identifier and
device serial number of its peer. The device model identifier and
device serial number of a backup device can also be provided. An
access control check is performed when certificates are exchanged.
The certificate subject name must match one of these configured

values, and the certification path must validate to a configured
trust anchor, such as the GigaBeam Root CA, using the validation
rules in [PKIX1].

4.2. Oakley Groups

With IKE, several possible Diffie-Hellman groups are supported.
These groups originated with the Oakley protocol and are therefore
called "Oakley Groups".

GigaBeam devices use group 14, which is described in Section 3 of
[MODP].

4.3. Security Protocol Identifier

The ISAKMP proposal syntax was specifically designed to allow for the
simultaneous negotiation of multiple Phase 2 security protocol
suites. The identifiers for the IPsec Domain of Interpretation (DOI)
are given in [IPDOI].

The GigaBeam custom security protocol has been assigned the
PROTO_GIGABEAM_RADIO protocol identifier, with a value of 5.

The PROTO_GIGABEAM_RADIO specifies the use of the GigaBeam radio link
frame structure, which uses a single algorithm for both
confidentiality and authentication. The following table indicates
the algorithm values that are currently defined.

    Transform ID   Value
    ------------   -----
    RESERVED   0
    GIGABEAM_AES128_GCM   1

4.4. Keying Material

GIGABEAM_AES128_GCM requires 20 octets of keying material (called
KEYMAT in [IKE]). The first 16 octets are the 128-bit AES key, and
the remaining four octets are used as the salt value in the AES
counter block.

Presently, AES with a 128-bit key is the only encryption algorithm
that is supported. Other encryption algorithms could be registered
in the future.

4.5. Identification Type Values

   The following table lists the assigned values for the Identification
   Type field found in the ISAKMP Identification Payload.

      ID Type   Value
      -------   -----
      RESERVED   0
      ID_IPV4_ADDR   1
      ID_FQDN   2
      ID_USER_FQDN   3
      ID_IPV4_ADDR_SUBNET   4
      ID_IPV6_ADDR   5
      ID_IPV6_ADDR_SUBNET   6
      ID_IPV4_ADDR_RANGE   7
      ID_IPV6_ADDR_RANGE   8
      ID_DER_ASN1_DN   9
      ID_DER_ASN1_GN   10
      ID_KEY_ID   11

   The ID_DER_ASN1_DN will be used when negotiating security
   associations for use with the GigaBeam custom security protocol. The
   provided distinguished name must match the peer's subject name
   provided in the X.509 certificate.

4.6. Security Parameter Index

   The least significant bit of the Security Parameter Index (SPI) is
   used in the GigaBeam custom security protocol. When two GigaBeam
   custom security protocol security associations are active at the same
   time for communications in the same direction, the least significant
   bit of the SPI must be different to ensure that these active security
   associations can be distinguished by the single bit in the GigaBeam
   custom security protocol.

4.7. Key Management Latency

   The IKE exchange over the DCC must complete before subscriber data
   can be exchanged in the GigaBeam radio link frame payload. Since
   each radio link frame carries a small portion of an IP datagram, many
   radio link frames carrying all zero bits must be sent and received to
   complete the IKE exchange.

   Once the initial keying material is in place, the IKE exchanges to
   establish subsequent keying material can be performed concurrent with
   the transfer of subscriber data in the radio link frame payload. The
   KEYSEL field in the radio link frame is used to indicate which keying
   material is being used.

The PN field in radio link frame provides a continuous indication of
the number of frames that have been encrypted with a particular key.
Once a threshold is exceeded, the IKE exchanges begin to establish
the replacement keying material. Currently, the exchanges begin when
half of the packet numbers have been used, but any threshold can be
employed, as long as the replacement keying material is available
before the packet counters are exhausted.

5. Security Considerations

The security considerations in [IKE], [OAKLEY], [PKCS1], and [ESP]
apply to the security system defined in this document.

Confidentiality and integrity are provided by the use of negotiated
algorithms. AES-GCM [GCM] is used with the GigaBeam custom security
protocol to provide confidentiality and integrity protection of
subscriber traffic on the radio link. AES-CBC [CBC] and HMAC-SHA-1
[HMAC] are used with IPsec ESP [ESP] to provide confidentiality and
integrity protection of management traffic between the radio control
modules.

AES-GCM makes use of AES Counter mode to provide confidentiality.
Unfortunately, it is very easy to misuse counter mode. If counter
block values are ever used for more than one frame with the same key,
then the same key stream will be used to encrypt both frames, and the
confidentiality guarantees are voided. Using AES Counter mode with
the same counter values to encrypt two plaintexts under the same key
leaks the plaintext. The automated key management described here is
intended to prevent this from ever happening.

Since AES has a 128-bit block size, regardless of the mode employed,
the ciphertext generated by AES encryption becomes distinguishable
from random values after 2^{64} blocks are encrypted with a single key.
Since the GigaBeam radio link frame allows for up to 2^{40} fixed-
length frames in a single security association, there is no
possibility for more than 2^{64} blocks to be encrypted with one key.

The lifetime of a particular AES key can be shorter than 2^{40} frames.
A smaller threshold can be used as a trigger to transition to the
next key. This capability allows straightforward implementation of
policies that require the key to be changed after a particular volume
of traffic or a particular amount of time.

There are fairly generic precomputation attacks against all block
cipher modes that allow a meet-in-the-middle attack against the key.
These attacks require the creation and searching of huge tables of
ciphertext associated with known plaintext and known keys. Assuming
that the memory and processor resources are available for a

precomputation attack, then the theoretical strength of AES Counter
mode (and any other block cipher mode) is limited to $2^{(n/2)}$ bits,
where n is the number of bits in the key. The use of long keys is
the best countermeasure to precomputation attacks. The unpredictable
nonce value in the counter block significantly increases the size of
the table that the attacker must compute to mount a successful
precomputation attack.

Rekeying with Quick Mode results in new keys to protect GigaBeam
radio link frames; however, these keys are generated from the same
Diffie-Hellman shared secret. In order to limit the amount of data
that would be exposed by the disclosure of this Diffie-Hellman shared
secret or the associated Diffie-Hellman private key, implementations
should periodically rekey using a new Phase 1 exchange.

Diffie-Hellman exponents used in IKE Phase 1 should be erased from
memory immediately after use. Likewise, AES and HMAC-SHA-1 keying
material should be erased from memory when it is no longer needed.

This security solution makes use of IKEv1 [IKE]. IKEv1 was selected
over IKEv2 [IKEv2] primarily due to the availability of an
implementation for the processing environment. The use of IKEv2
would provide some useful capabilities, such as Diffie-Hellman group
negotiation. These additional capabilities would not significantly
improve the security of the overall key management solution that runs
on the two-node IP network.

6. IANA Considerations

   IANA has assigned one IPsec Security Protocol Identifier in
   http://www.iana.org/assignments/isakmp-registry for
   PROTO_GIGABEAM_RADIO. It was assigned the value 5.

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