Reliable Data Transfer II

Antonio Carzaniga

Faculty of Informatics
University of Lugano

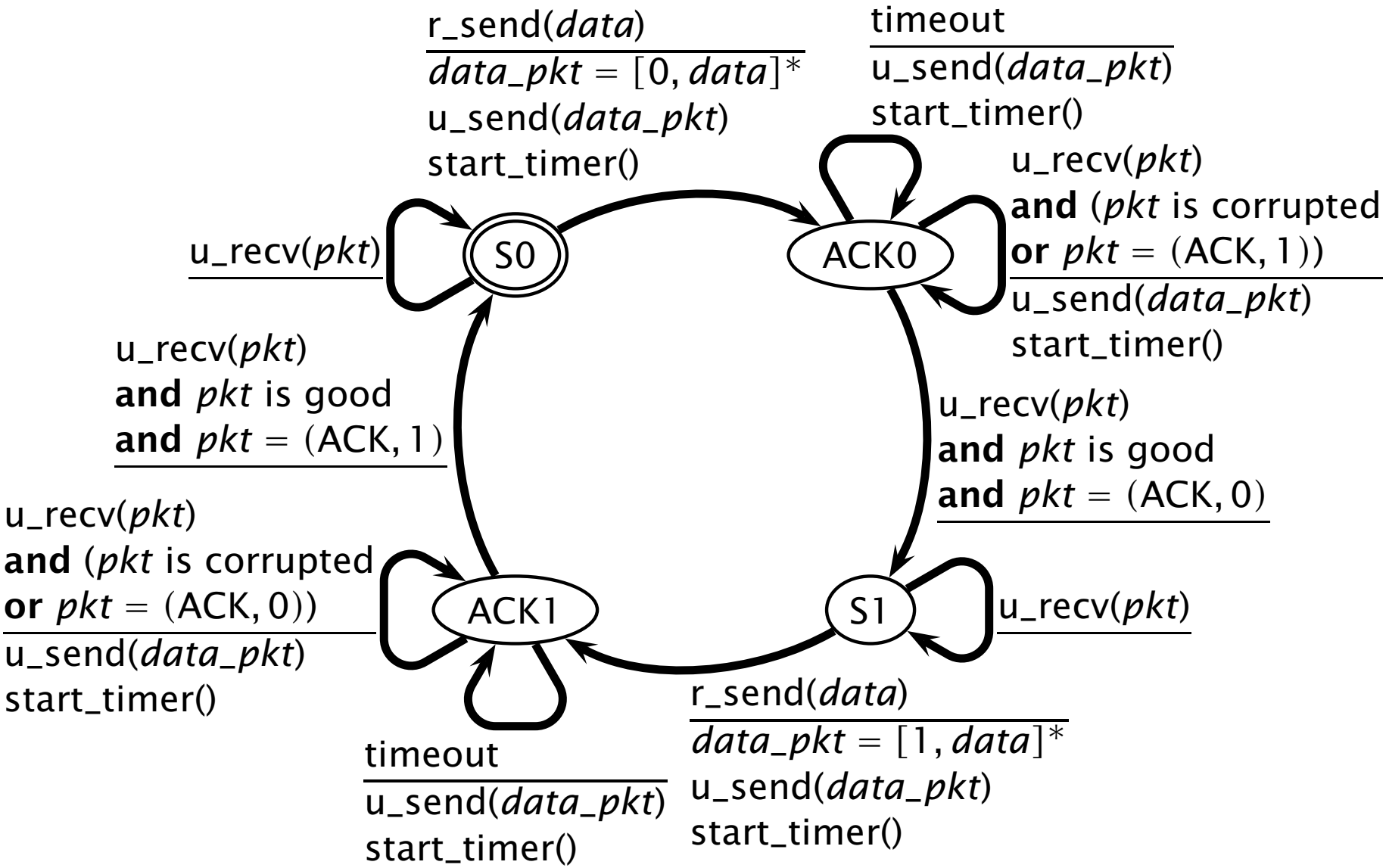
October 1, 2014

Outline

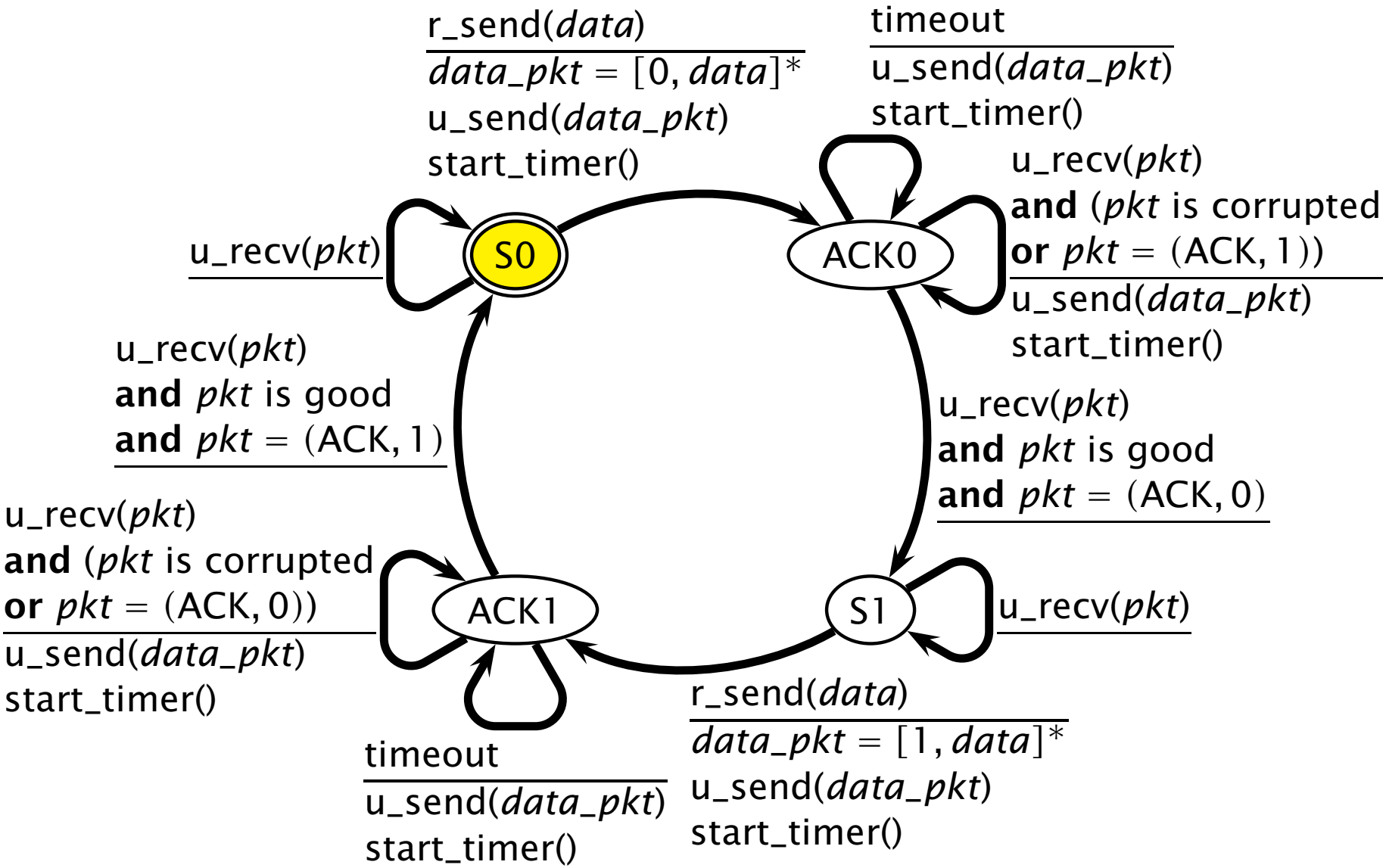
- Performance of the stop-and-wait protocol
- Go-Back-N
- Selective repeat

Back to Reliable Data Tranfer

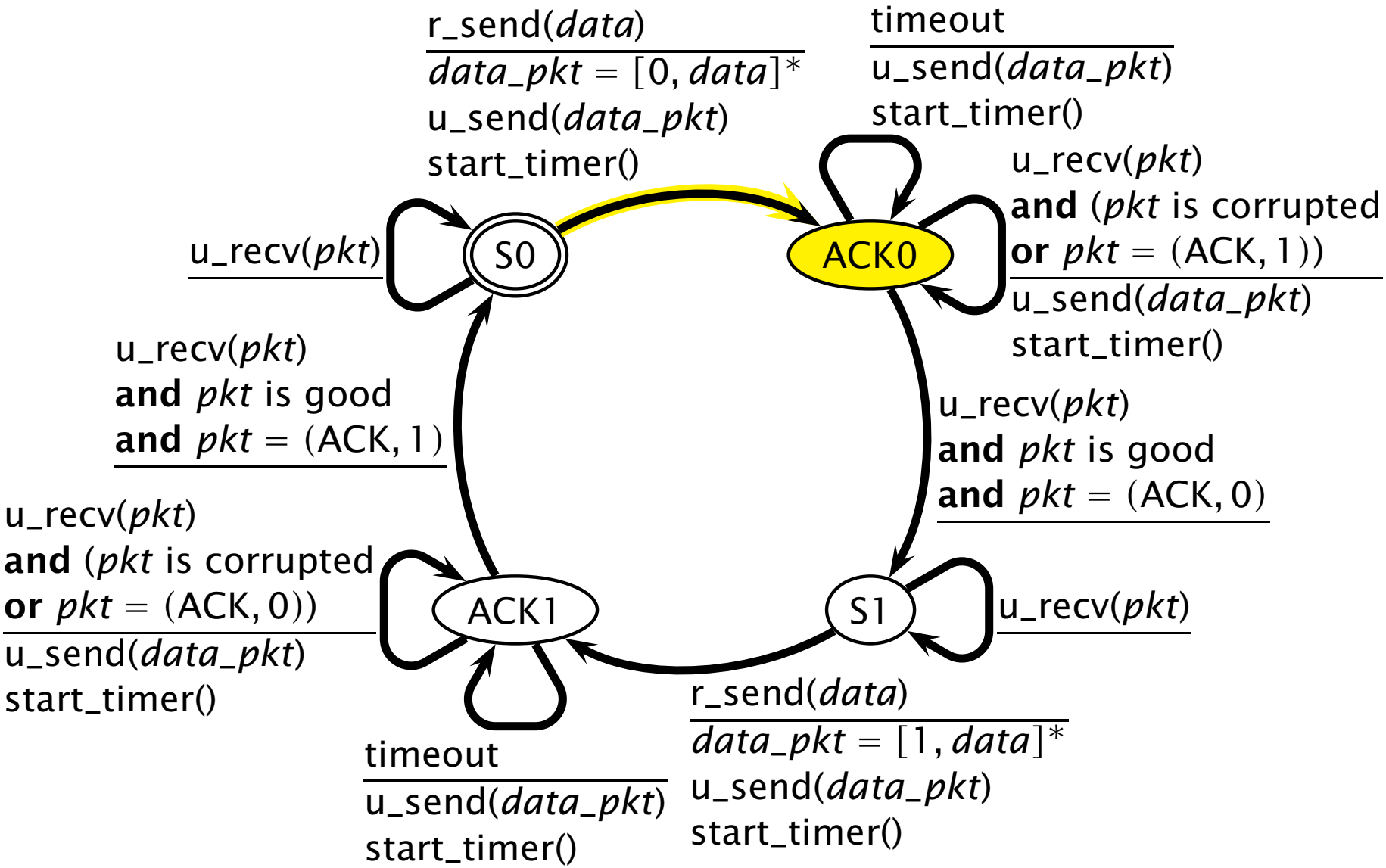
Back to Reliable Data Tranfer



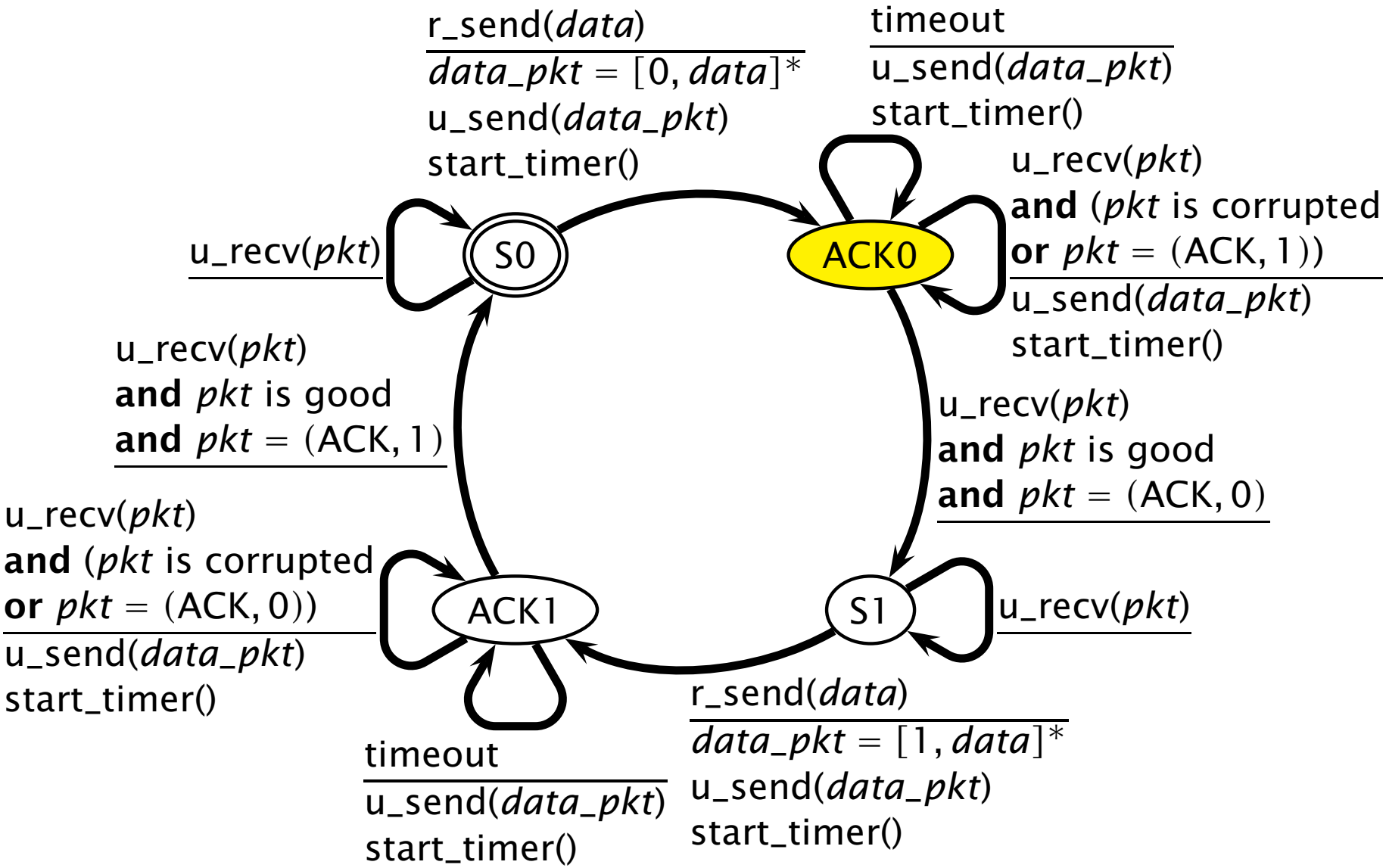
Back to Reliable Data Tranfer



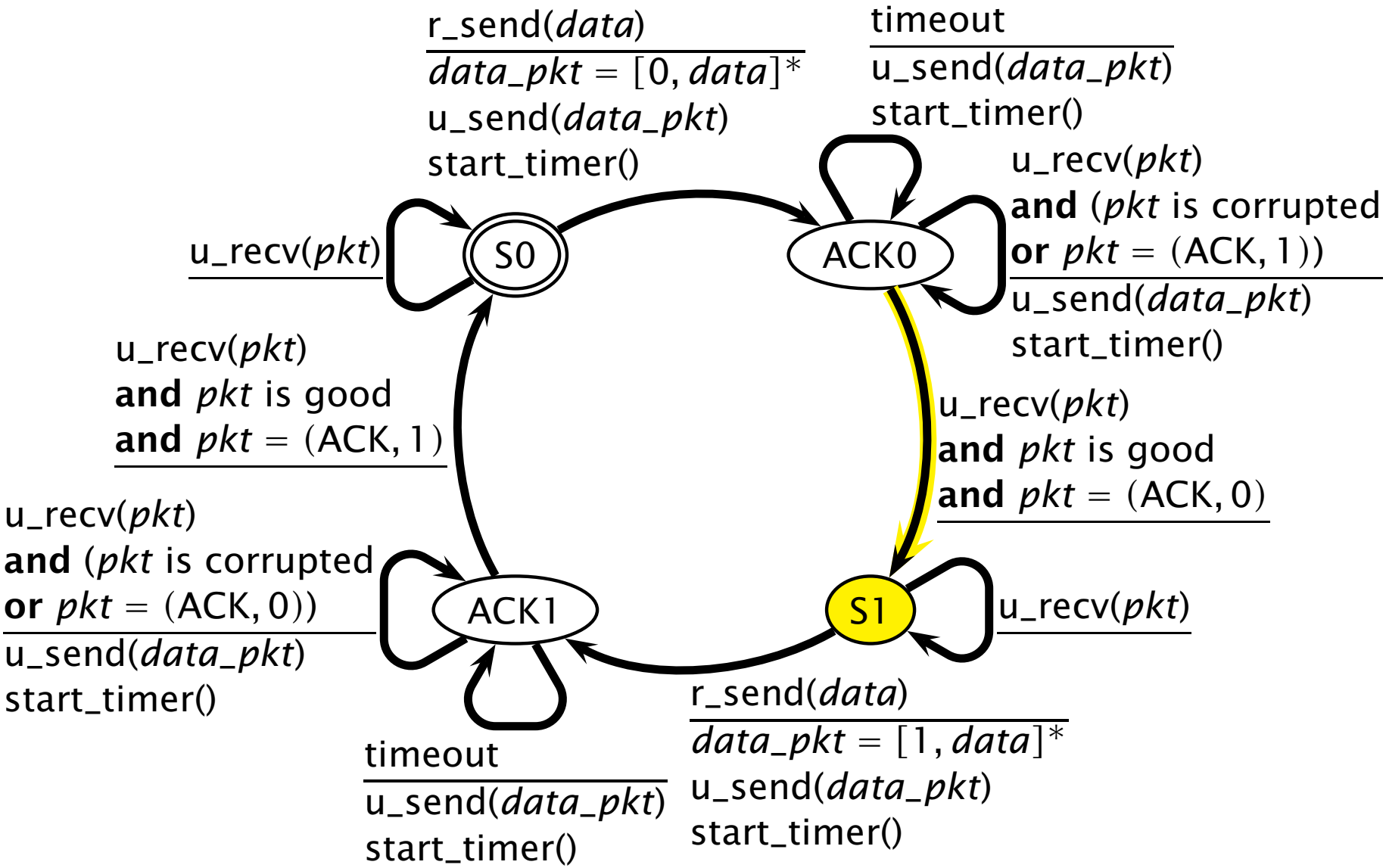
Back to Reliable Data Tranfer



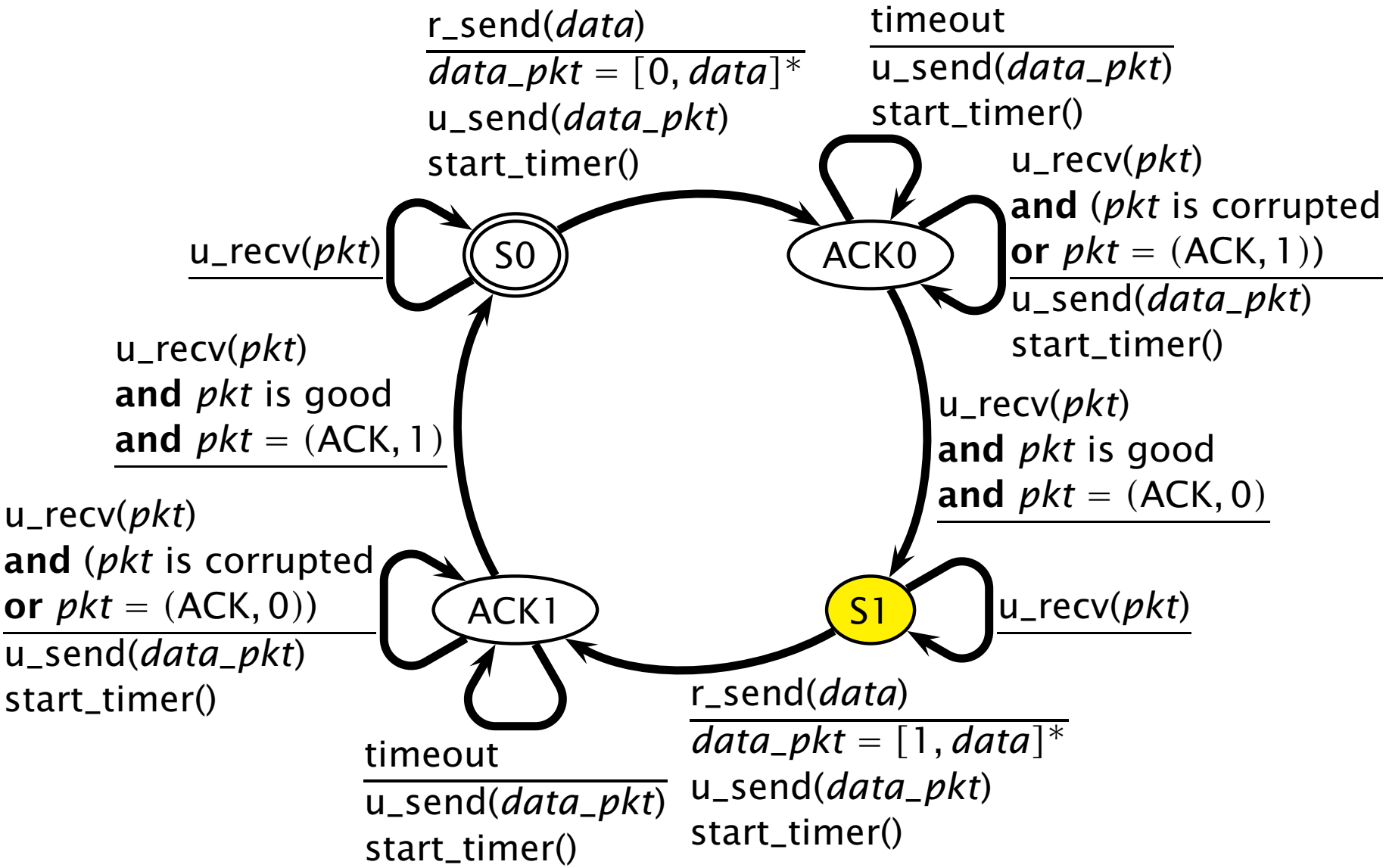
Back to Reliable Data Tranfer



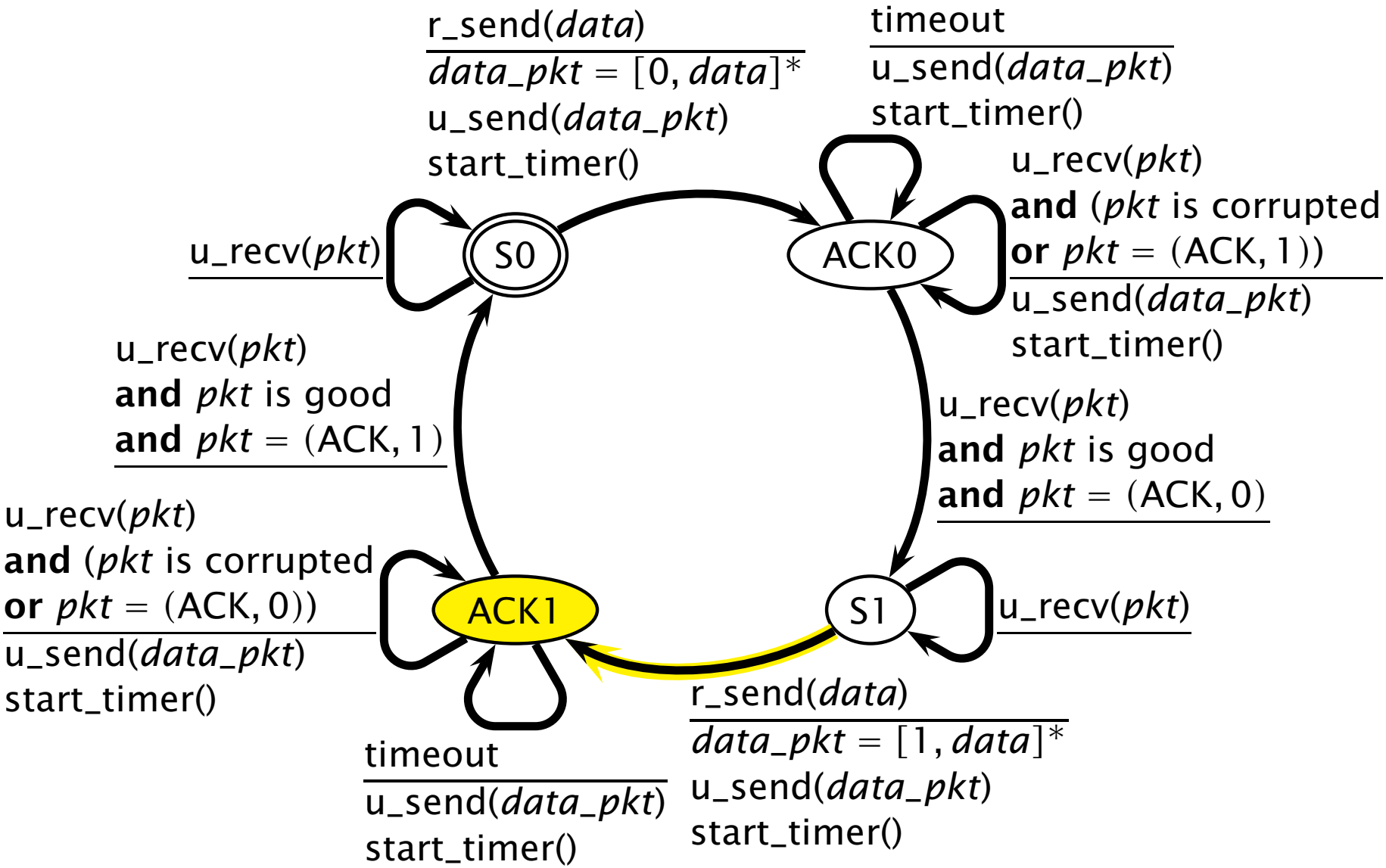
Back to Reliable Data Tranfer



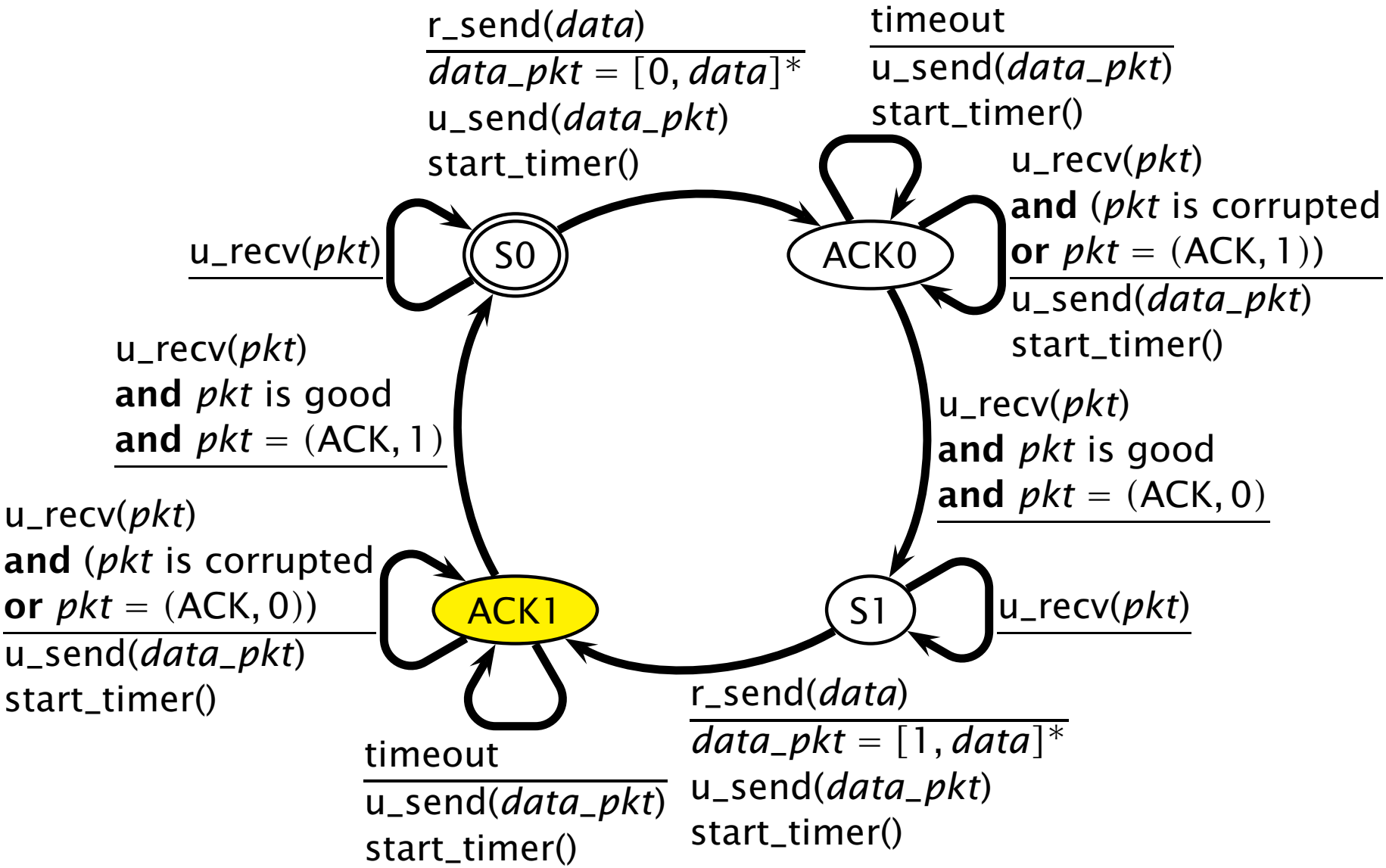
Back to Reliable Data Tranfer



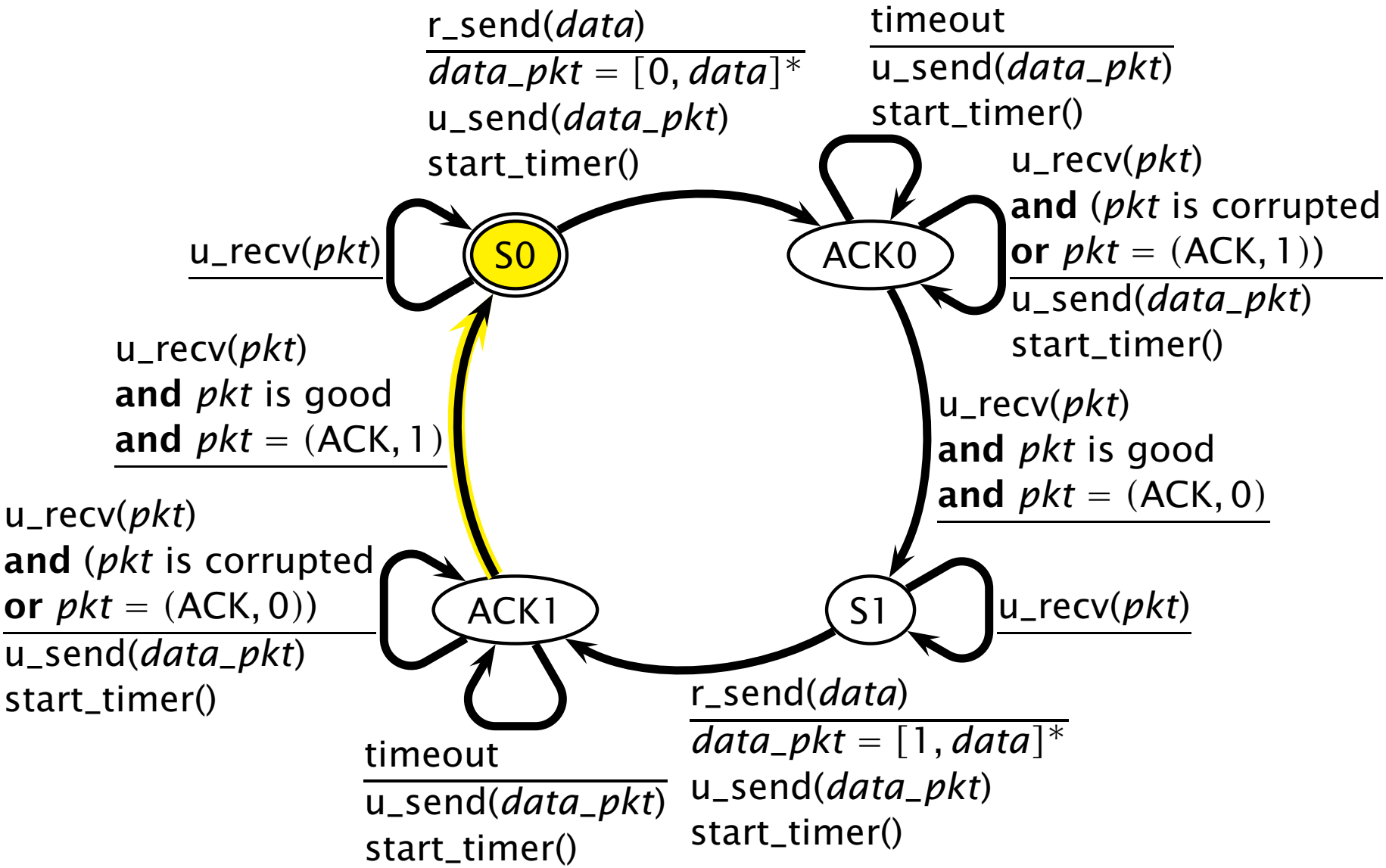
Back to Reliable Data Tranfer



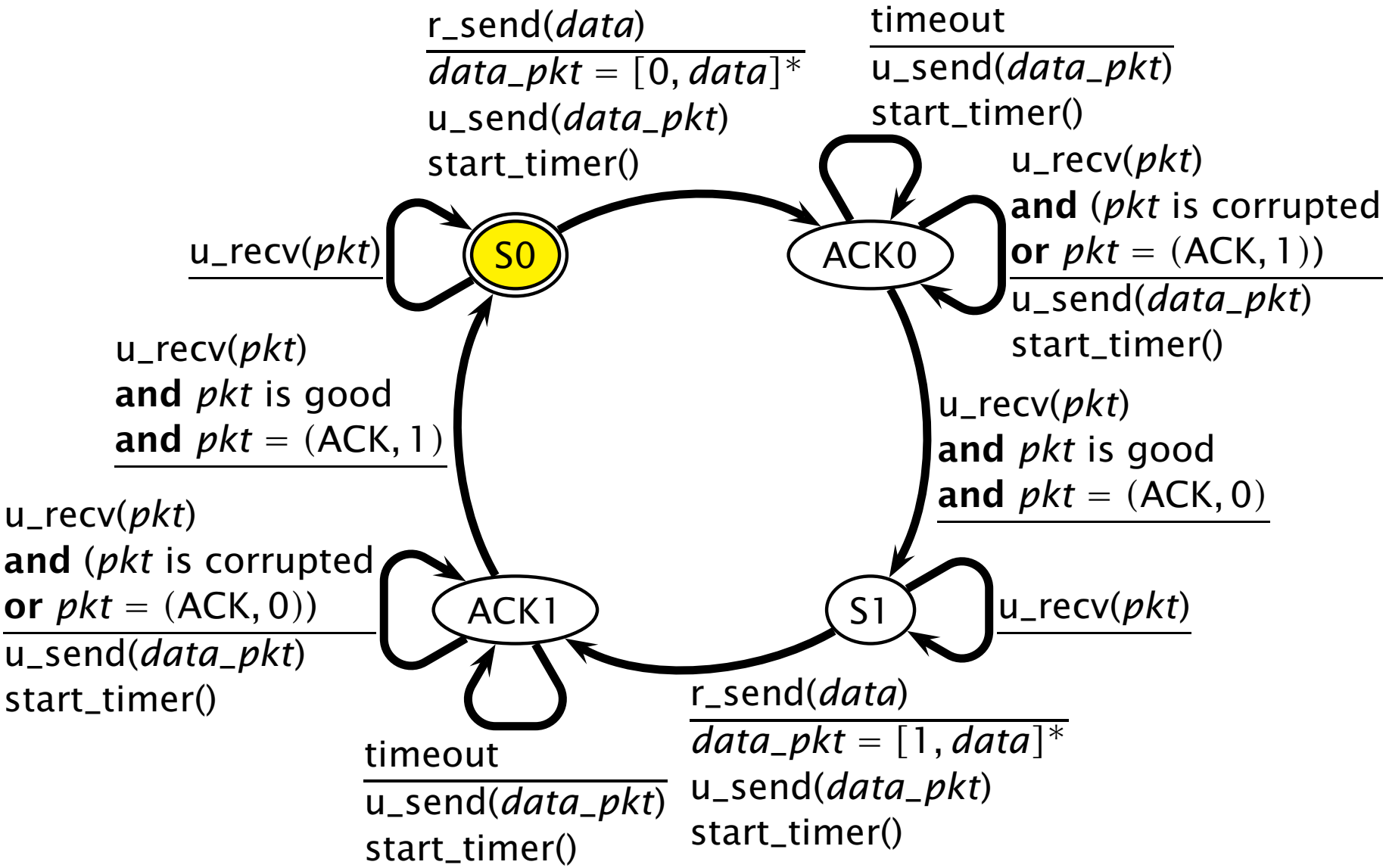
Back to Reliable Data Tranfer



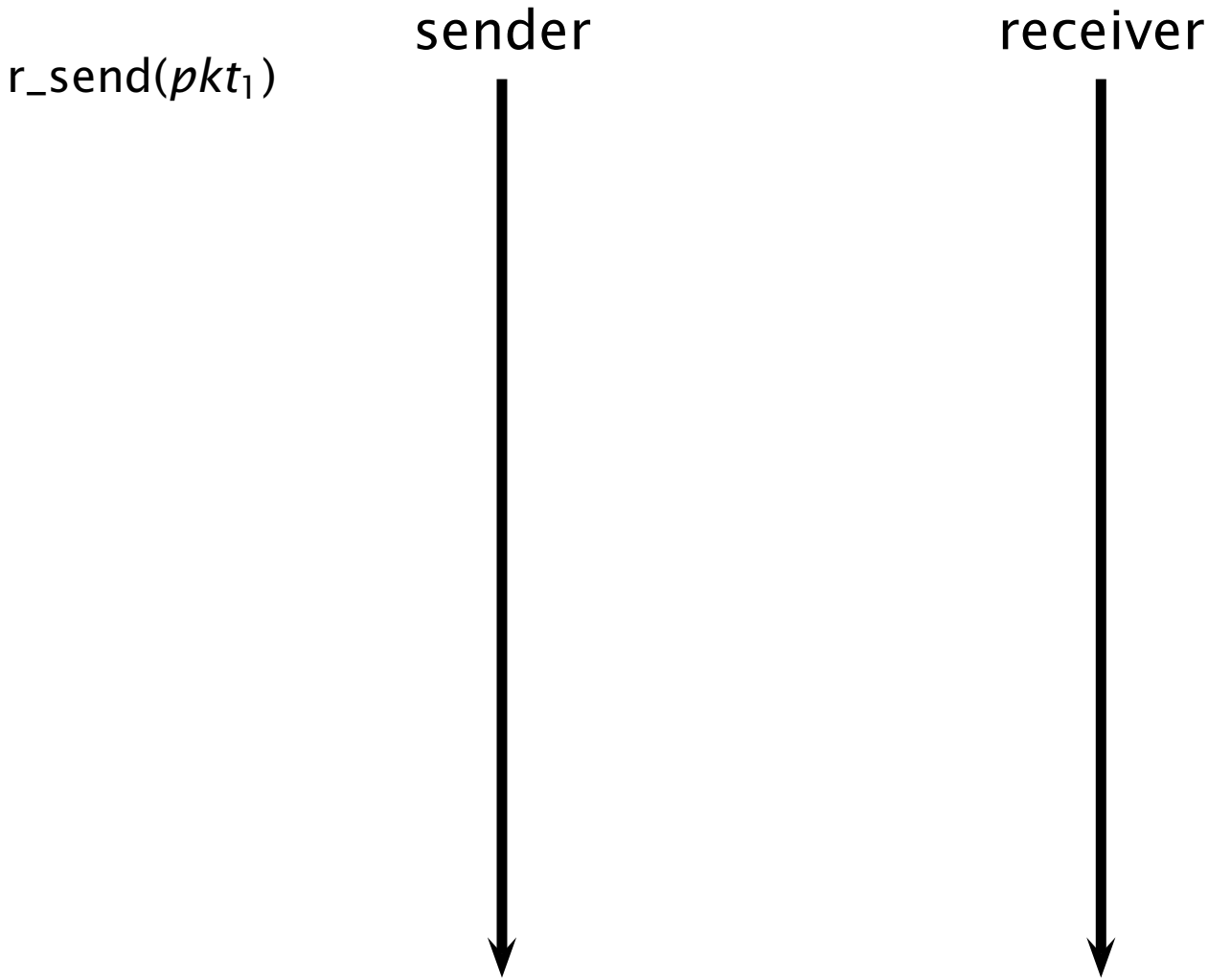
Back to Reliable Data Tranfer



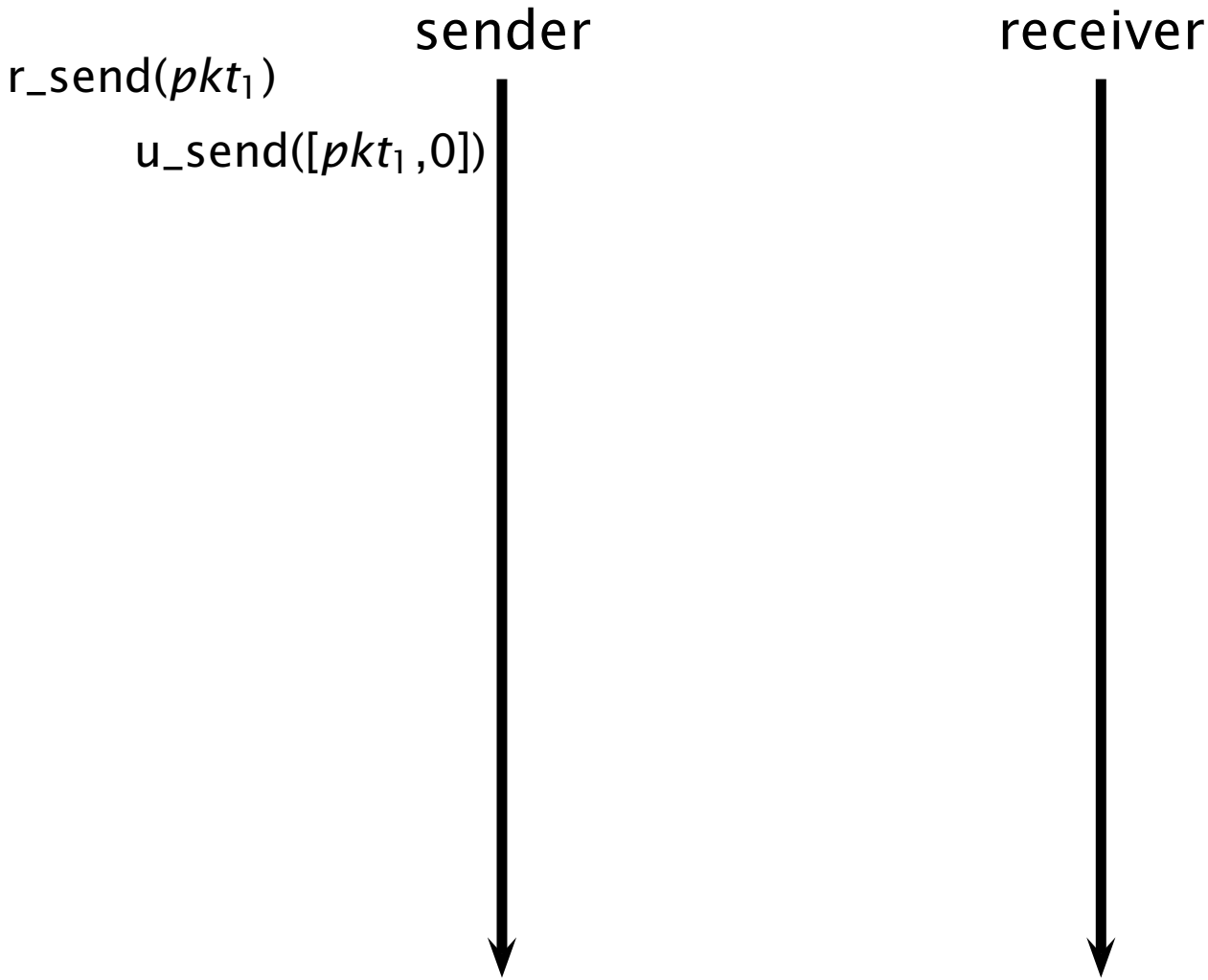
Back to Reliable Data Tranfer



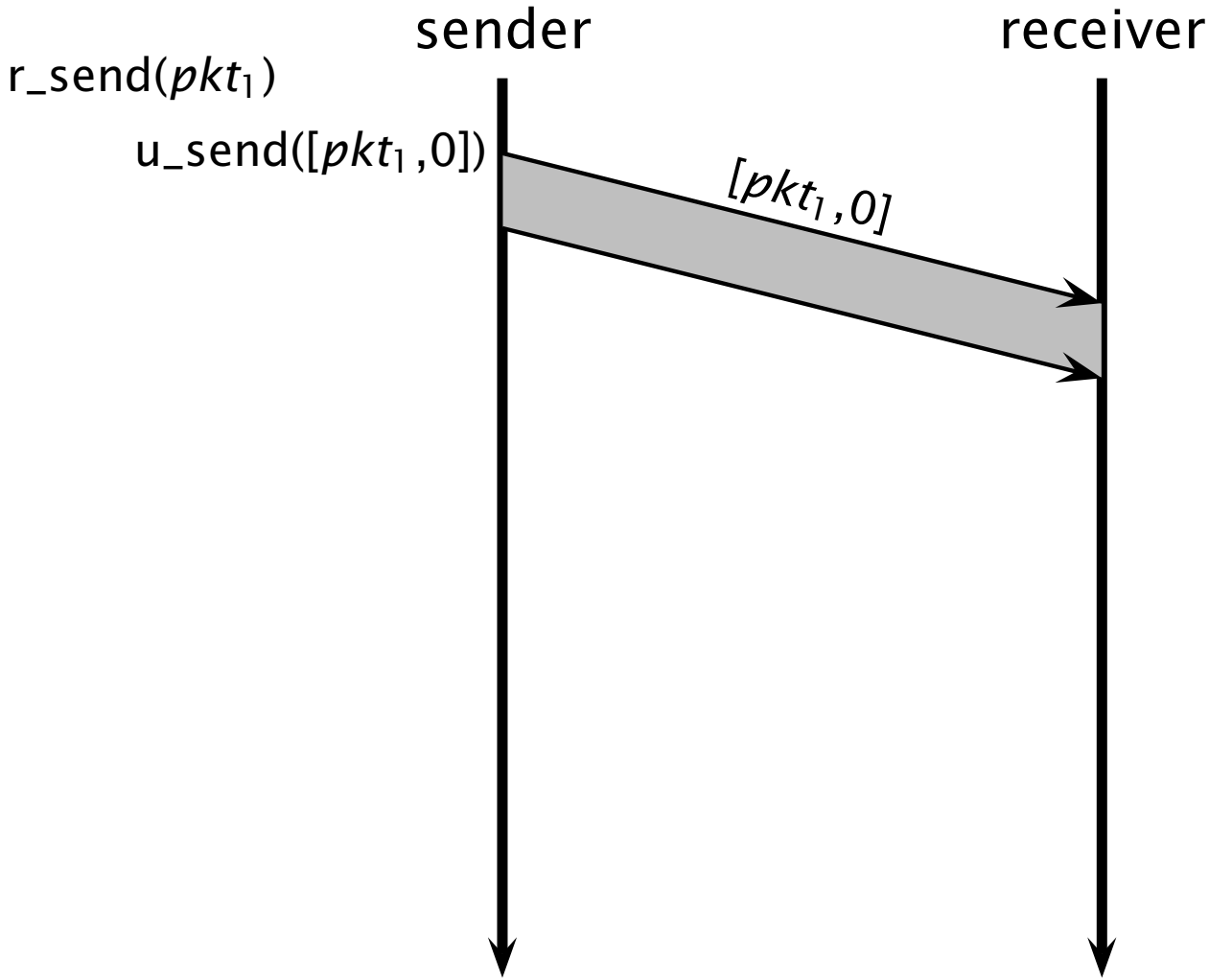
Network Usage



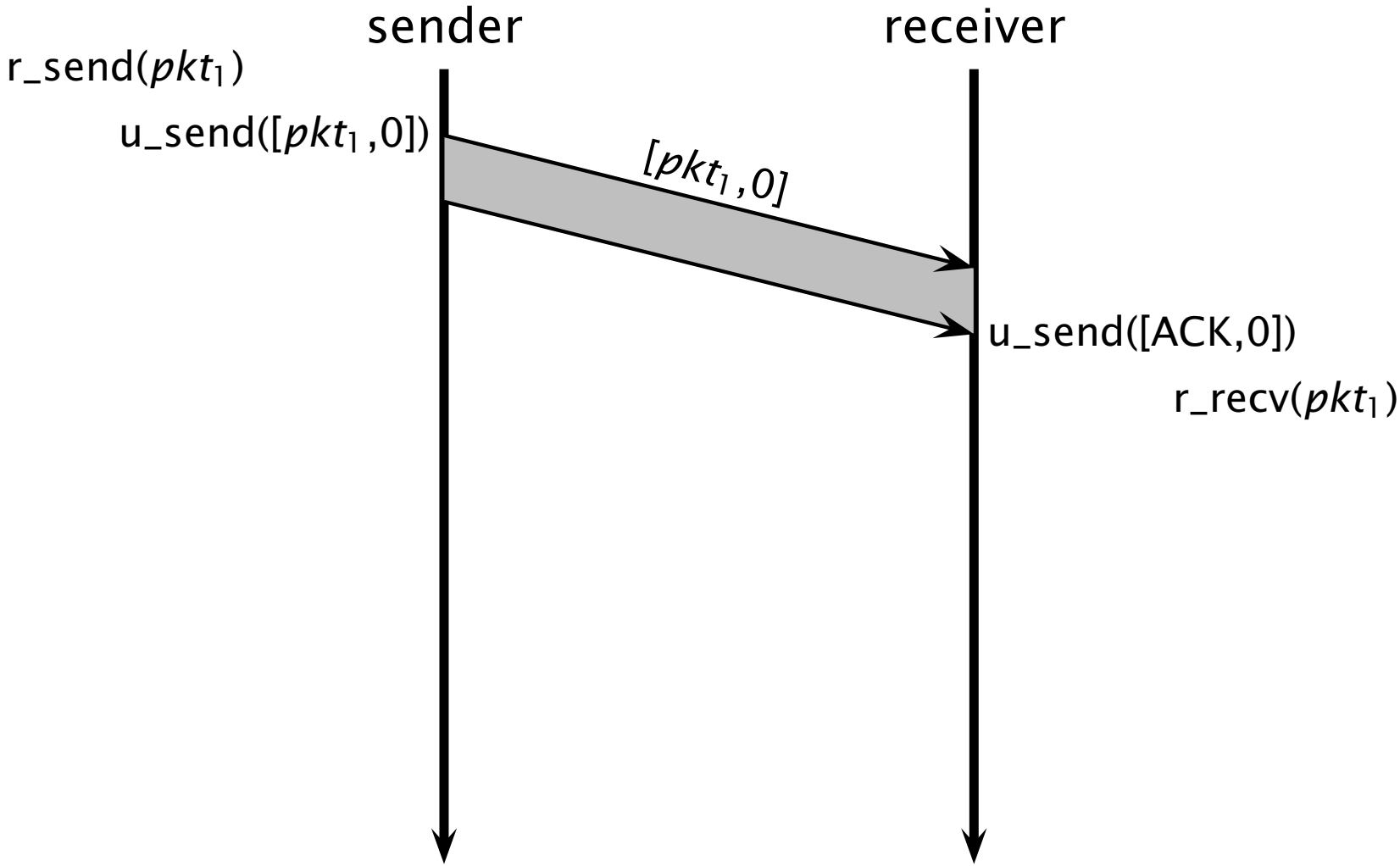
Network Usage



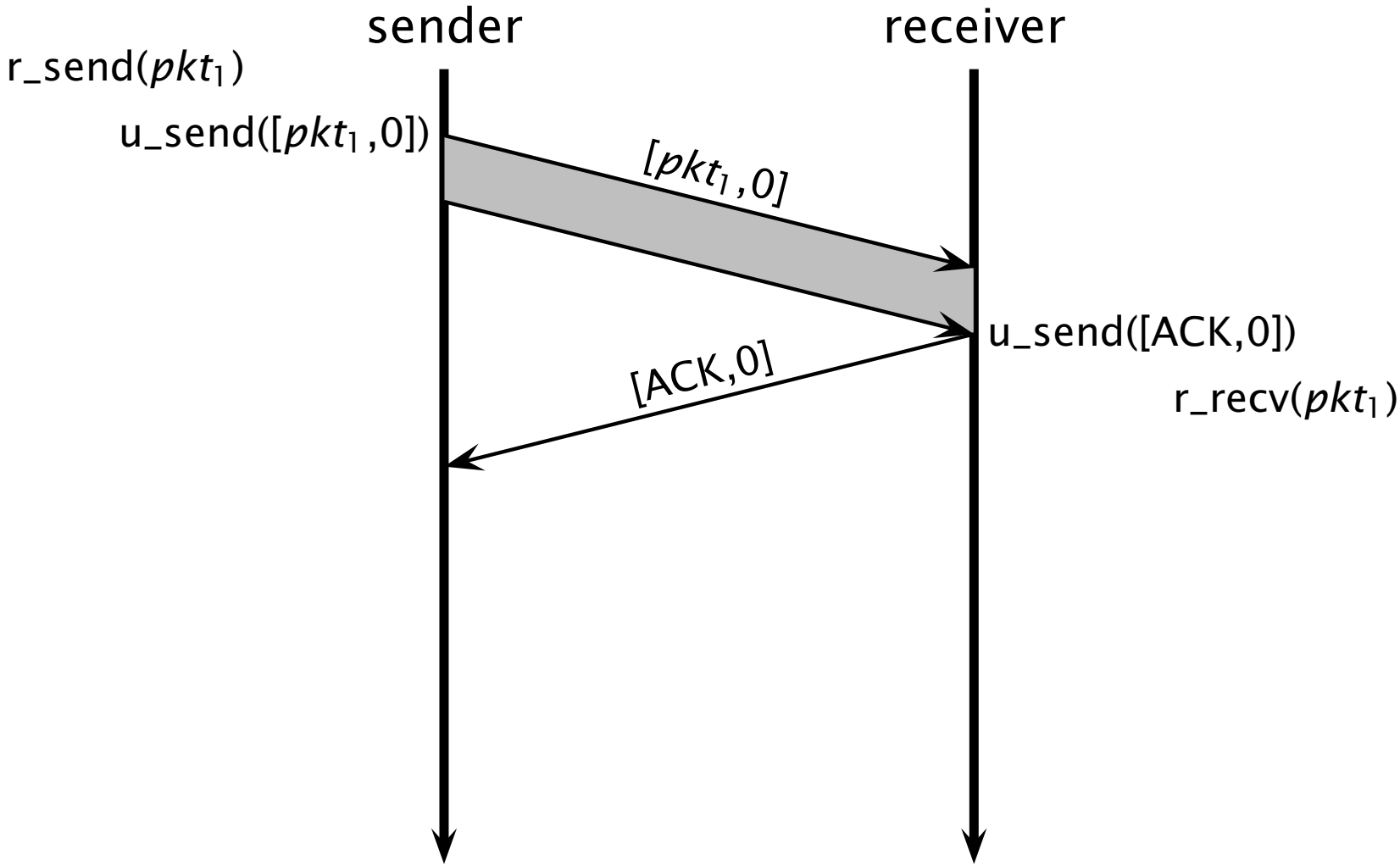
Network Usage



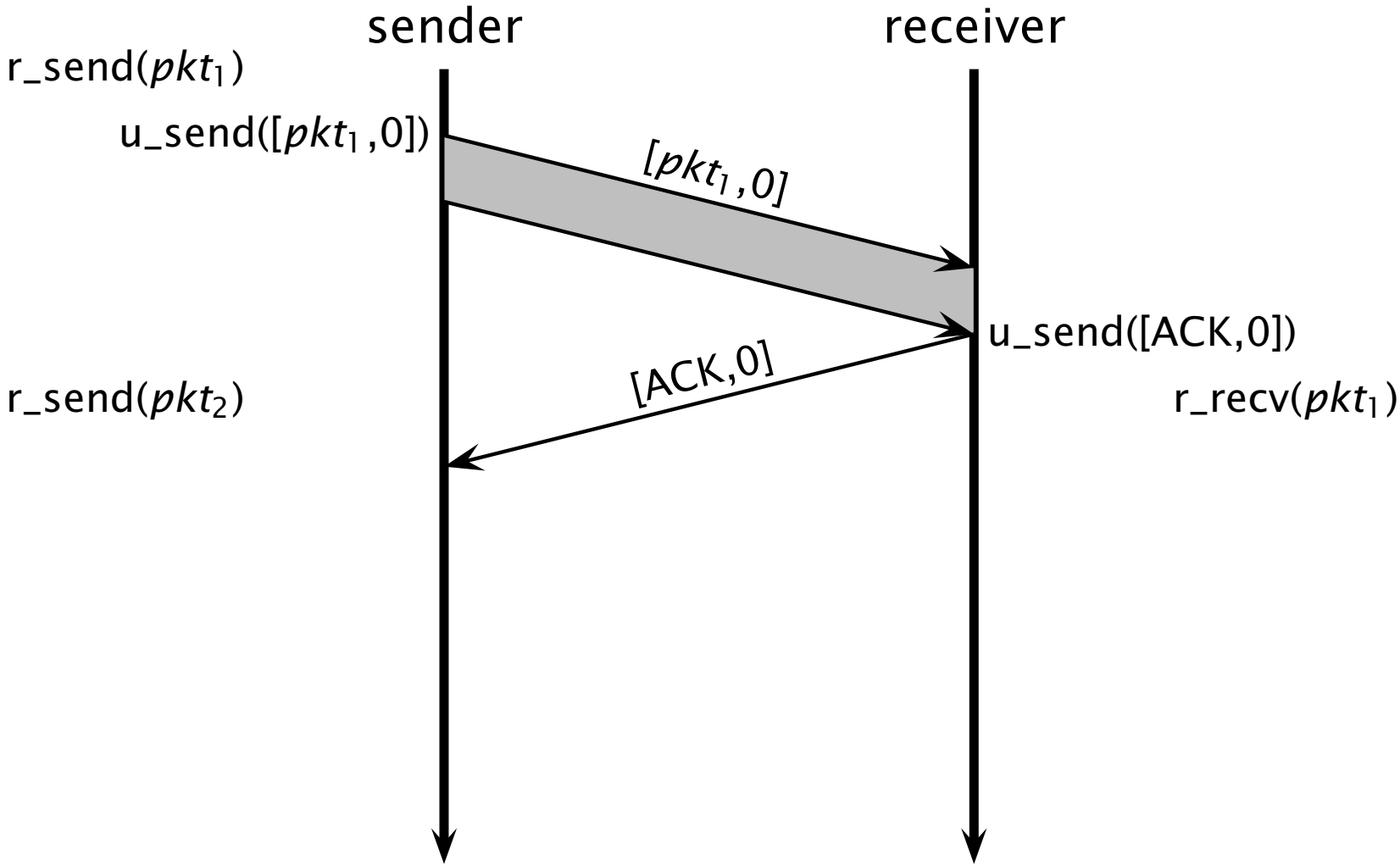
Network Usage



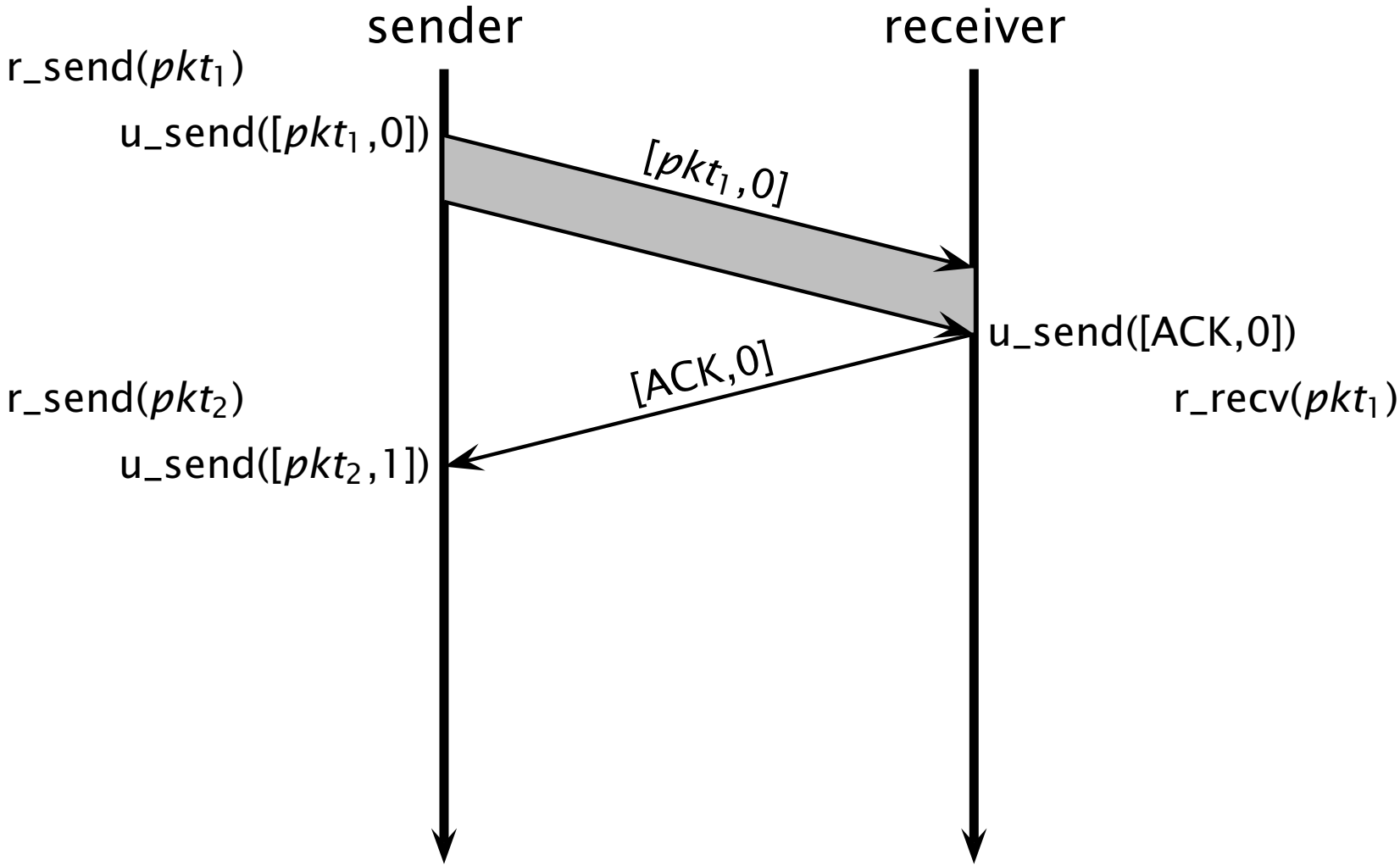
Network Usage



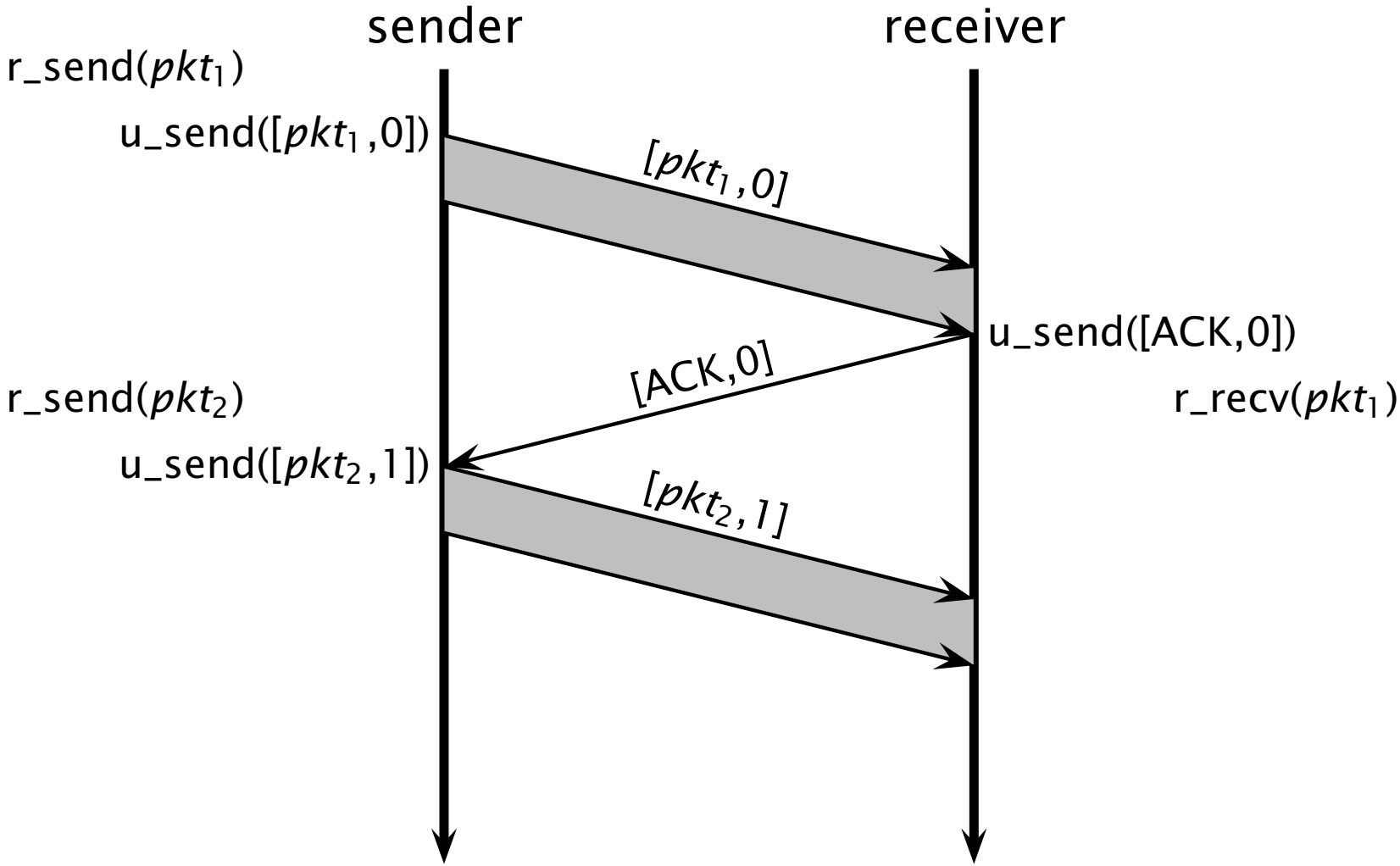
Network Usage



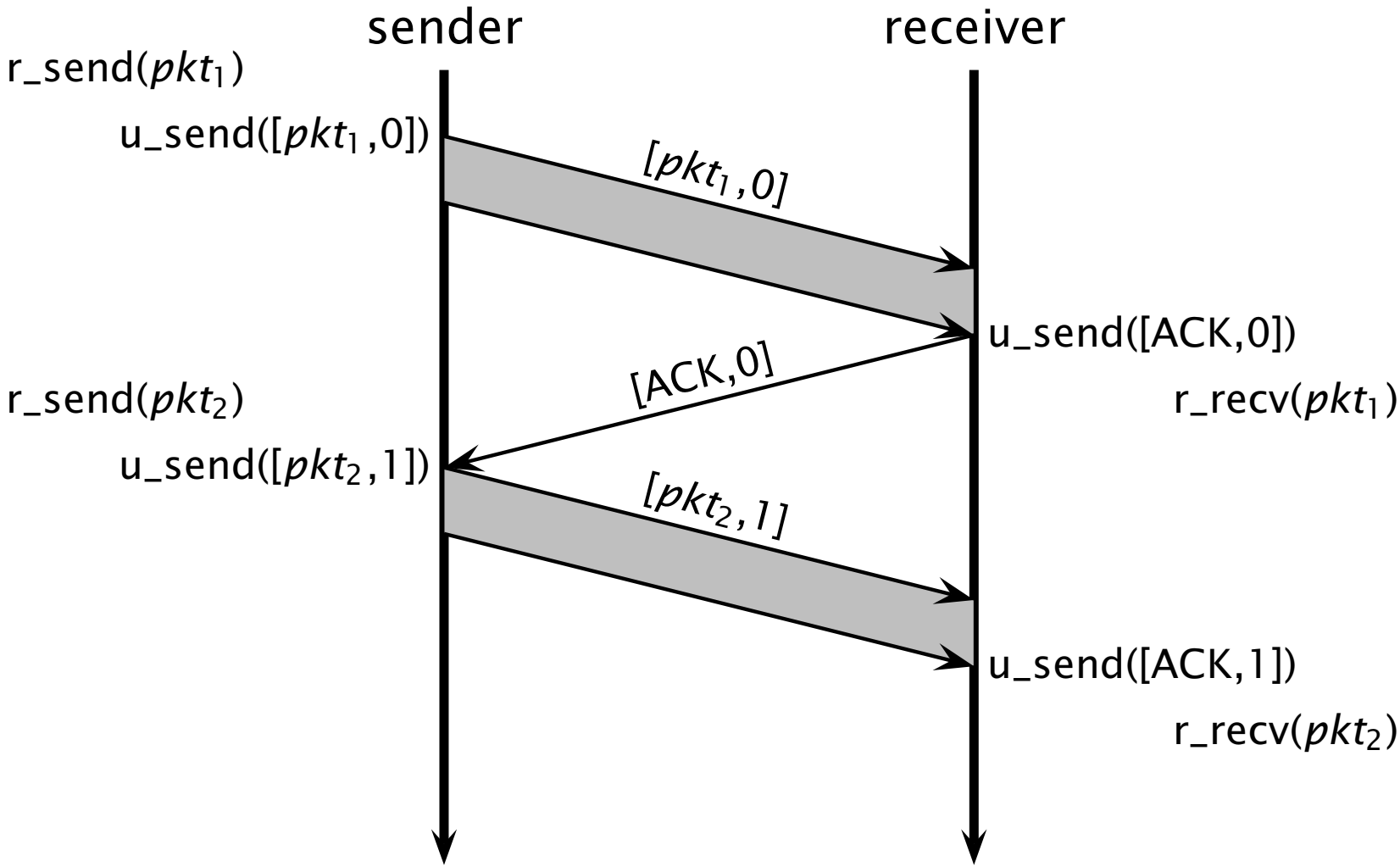
Network Usage



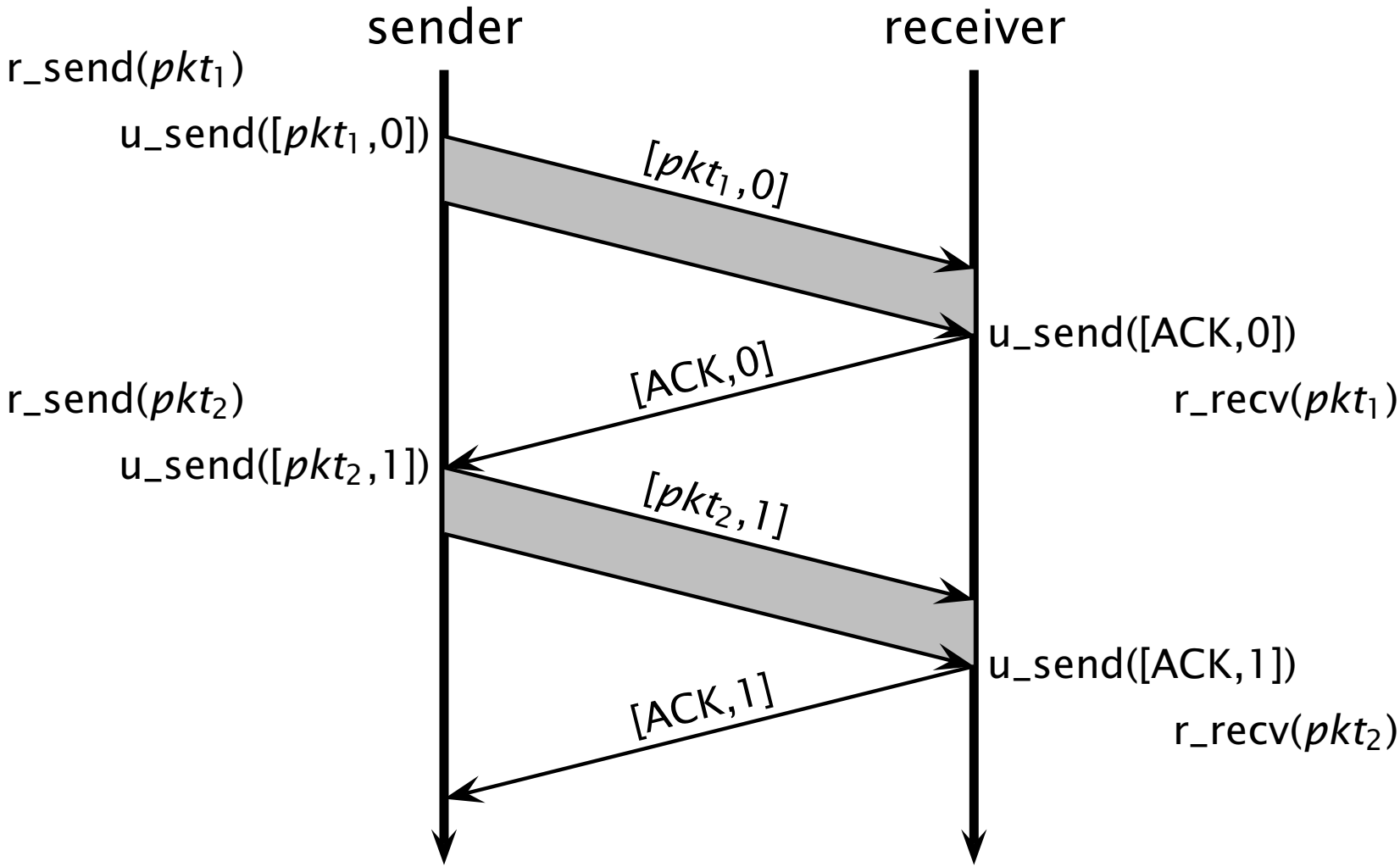
Network Usage



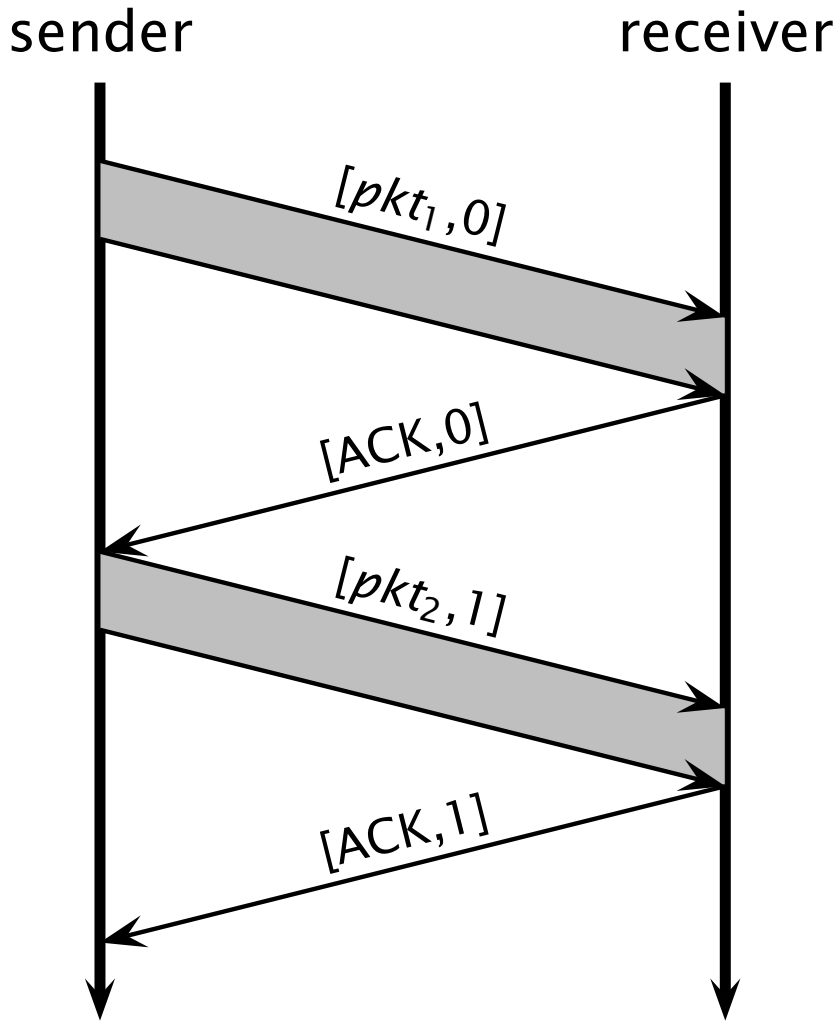
Network Usage



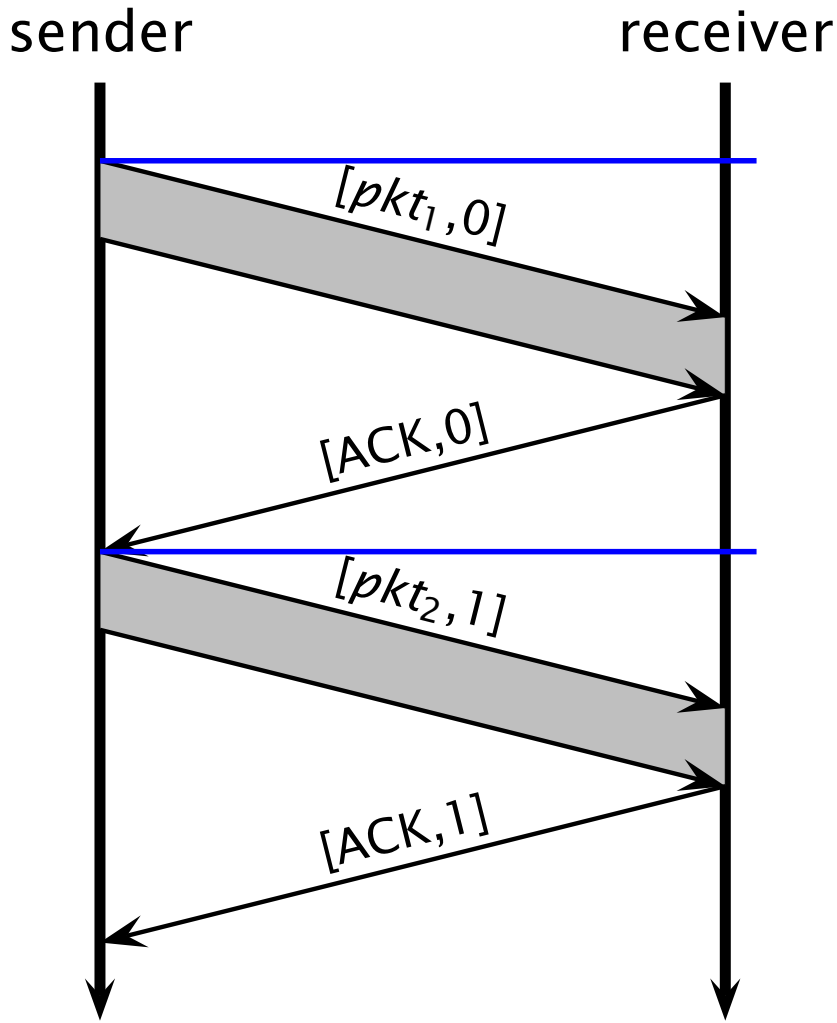
Network Usage



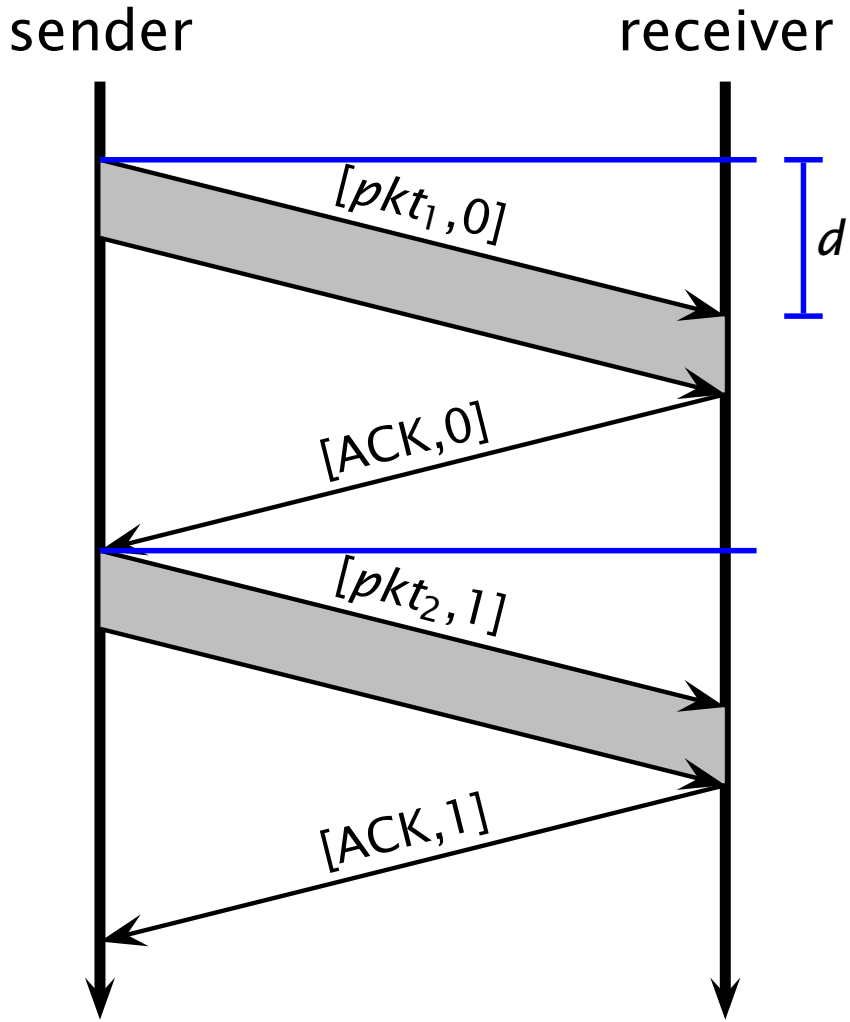
Network Usage



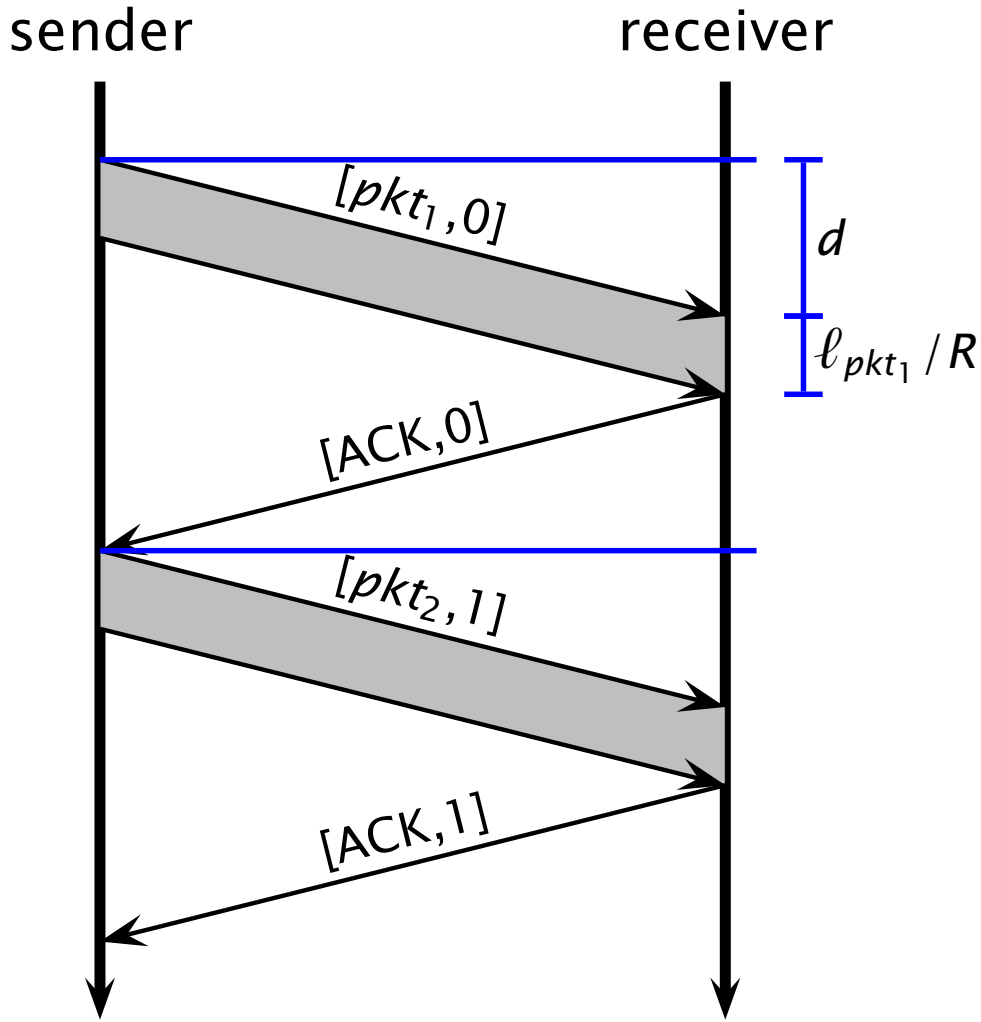
Network Usage



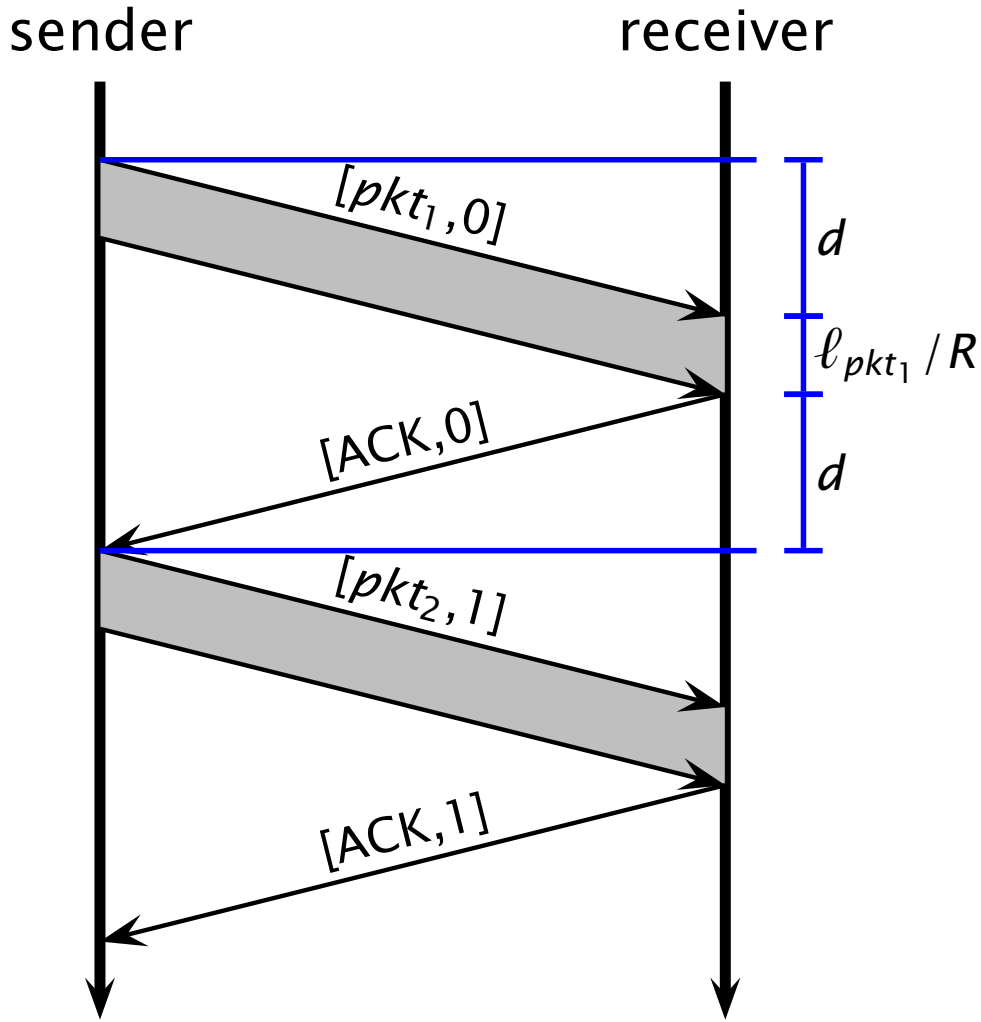
Network Usage



Network Usage



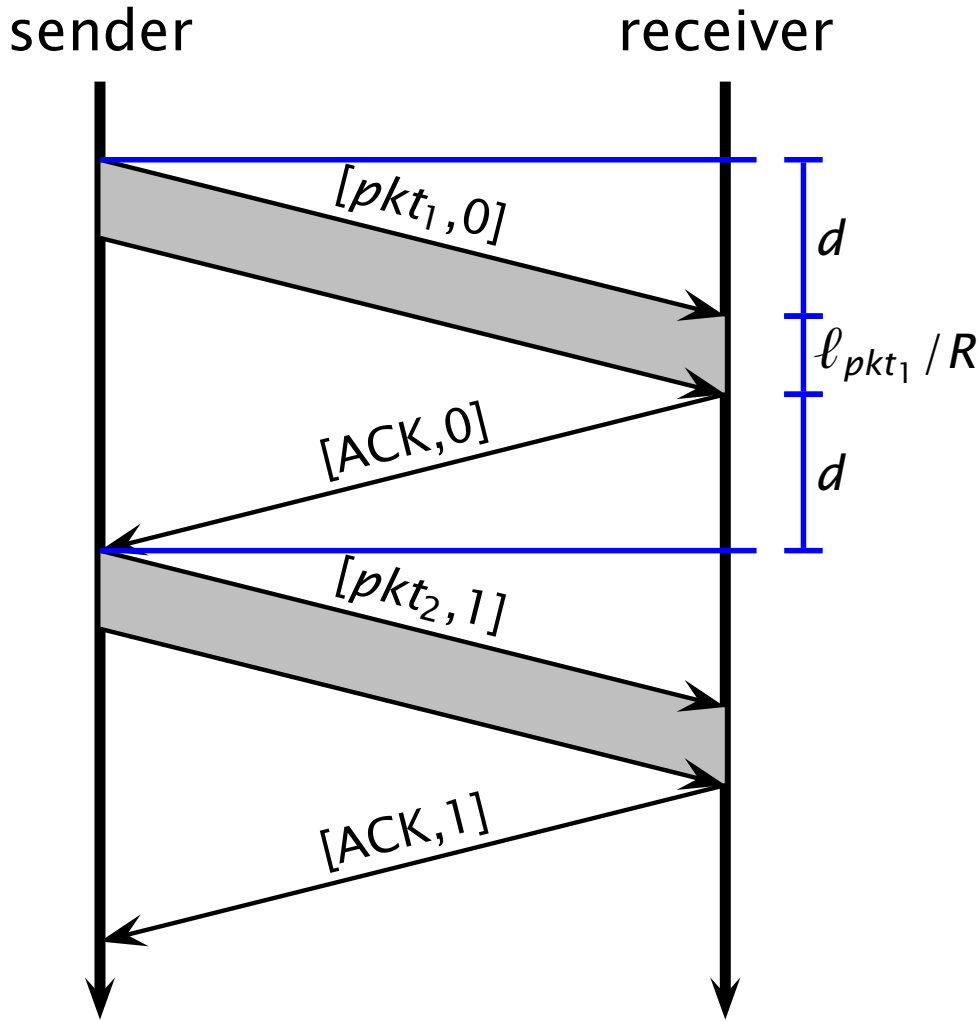
Network Usage



Network Usage

utilization factor

$$U = \frac{\ell_{pkt}/R}{2d+\ell_{pkt}/R}$$

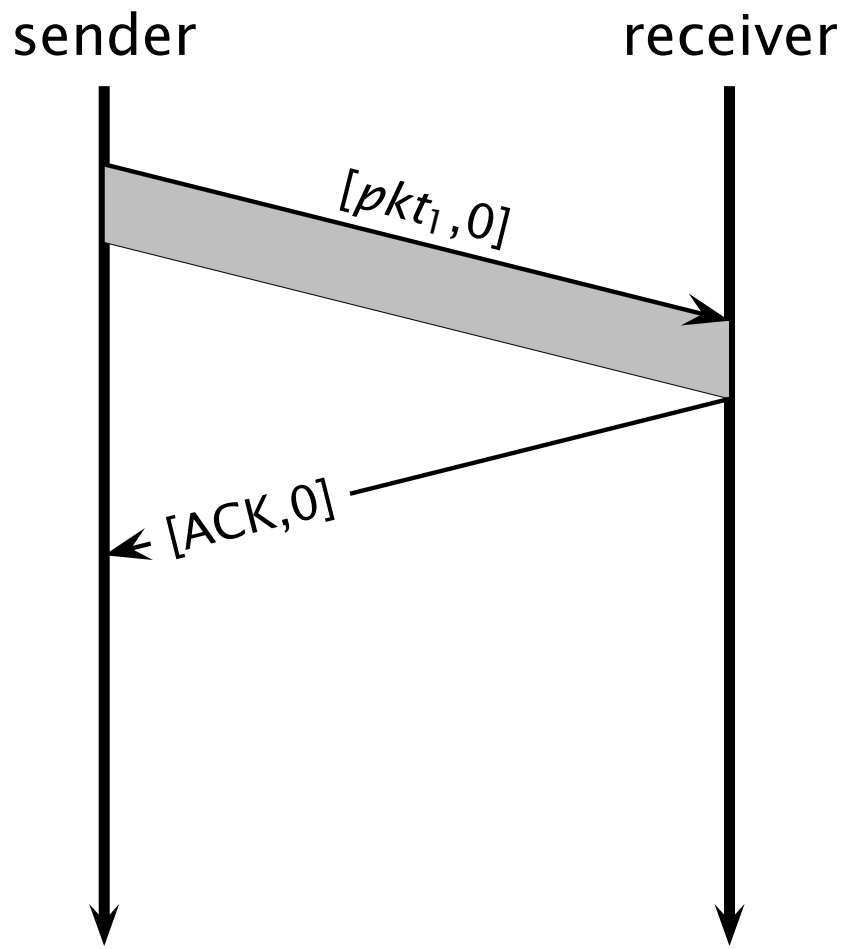


Improving Network Usage

- How do we achieve a better *utilization factor*?

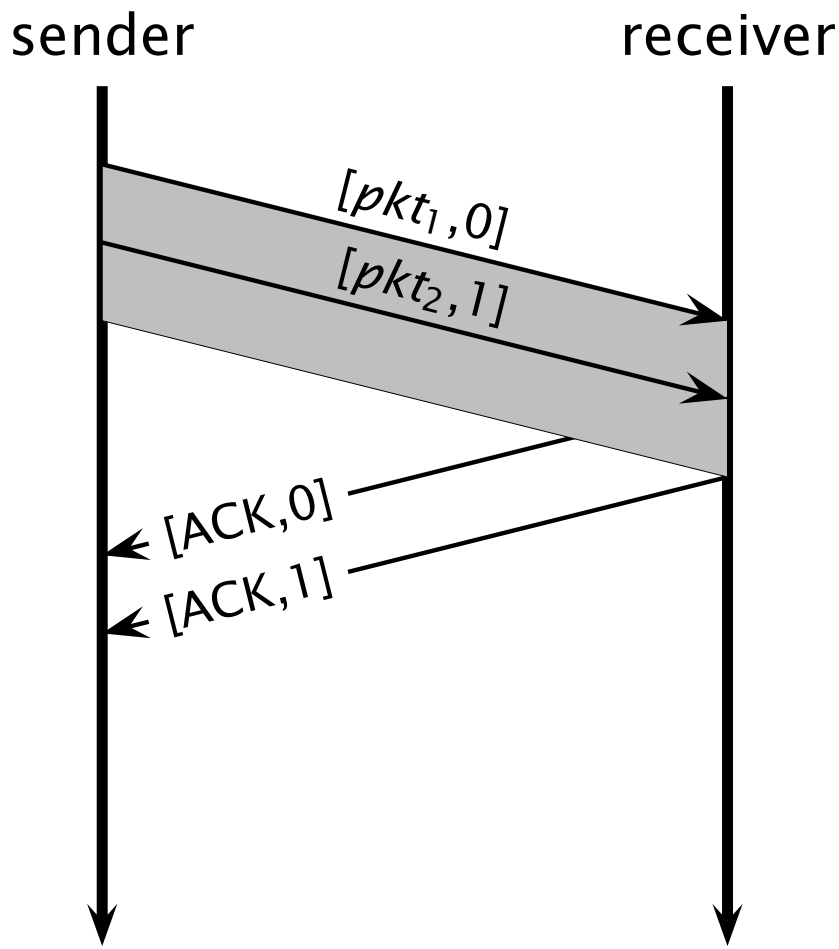
Improving Network Usage

- How do we achieve a better *utilization factor*?



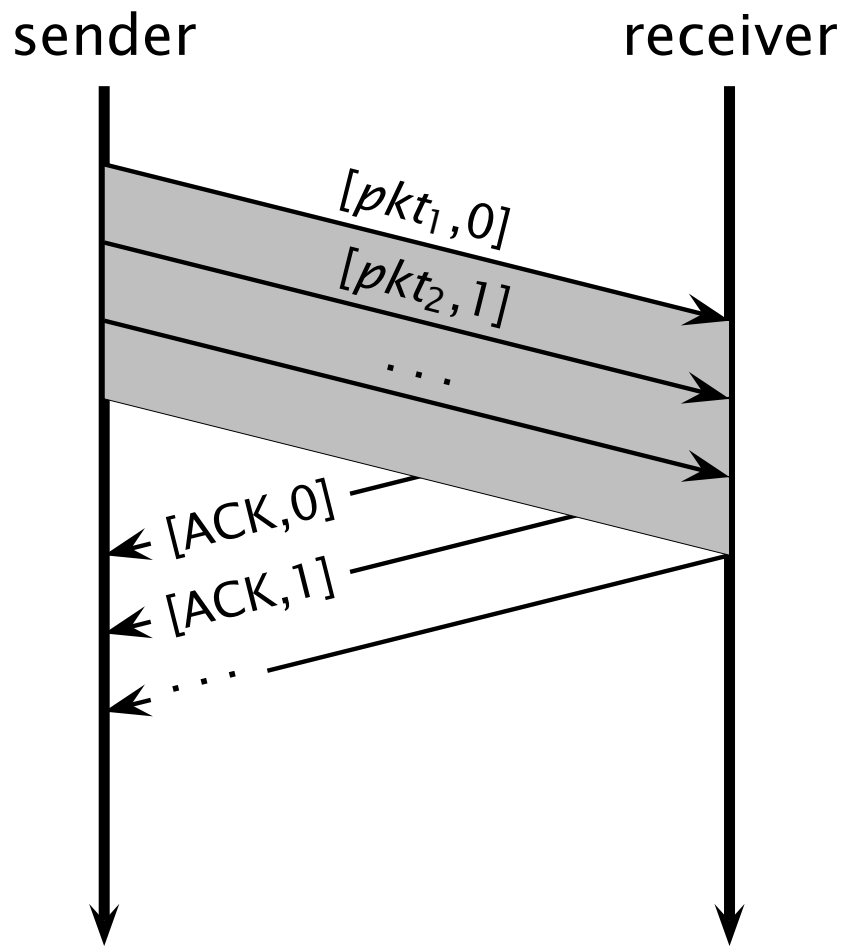
Improving Network Usage

- How do we achieve a better *utilization factor*?



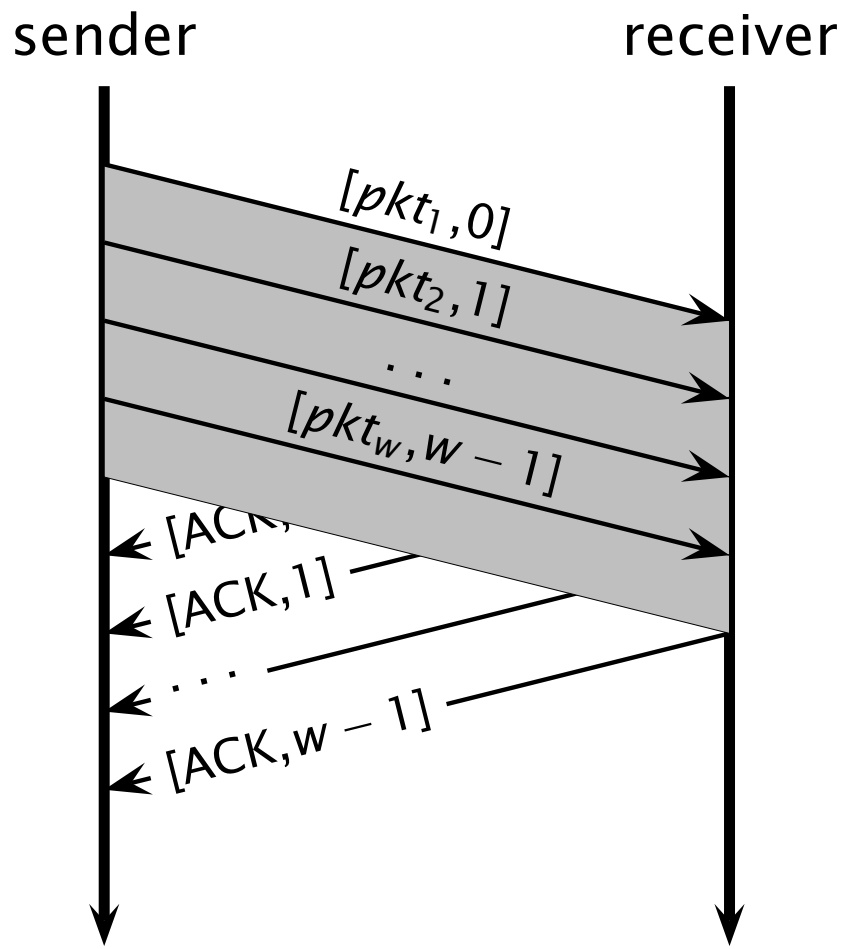
Improving Network Usage

- How do we achieve a better *utilization factor*?



Improving Network Usage

- How do we achieve a better *utilization factor*?



Go-Back-N

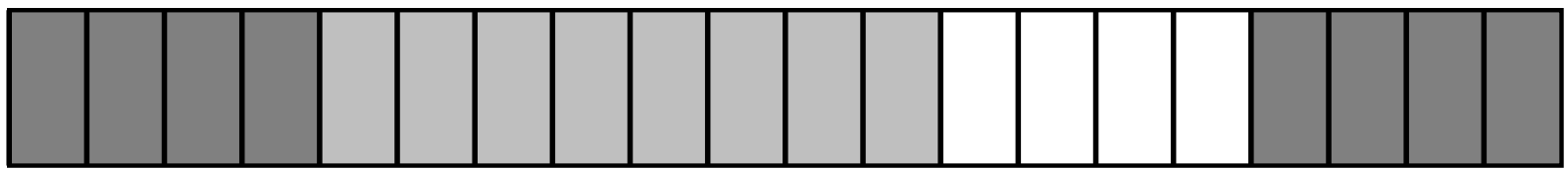
- **Idea:** the sender transmits multiple packets without waiting for an acknowledgement

Go-Back-N

- **Idea:** the sender transmits multiple packets without waiting for an acknowledgement
- Sender has up to *W* unacknowledged packets in the pipeline
  - the sender's state machine gets very complex
  - we represent the sender's state with its queue of acknowledgements

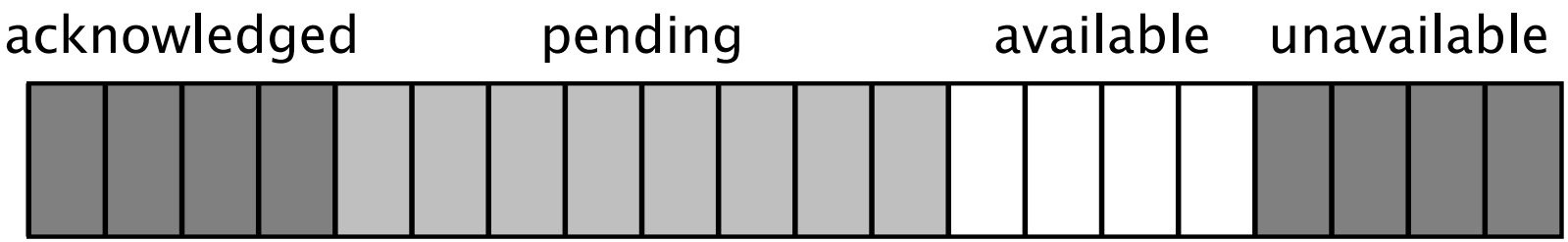
Go-Back-N

- **Idea:** the sender transmits multiple packets without waiting for an acknowledgement
- Sender has up to *W* unacknowledged packets in the pipeline
  - the sender's state machine gets very complex
  - we represent the sender's state with its queue of acknowledgements



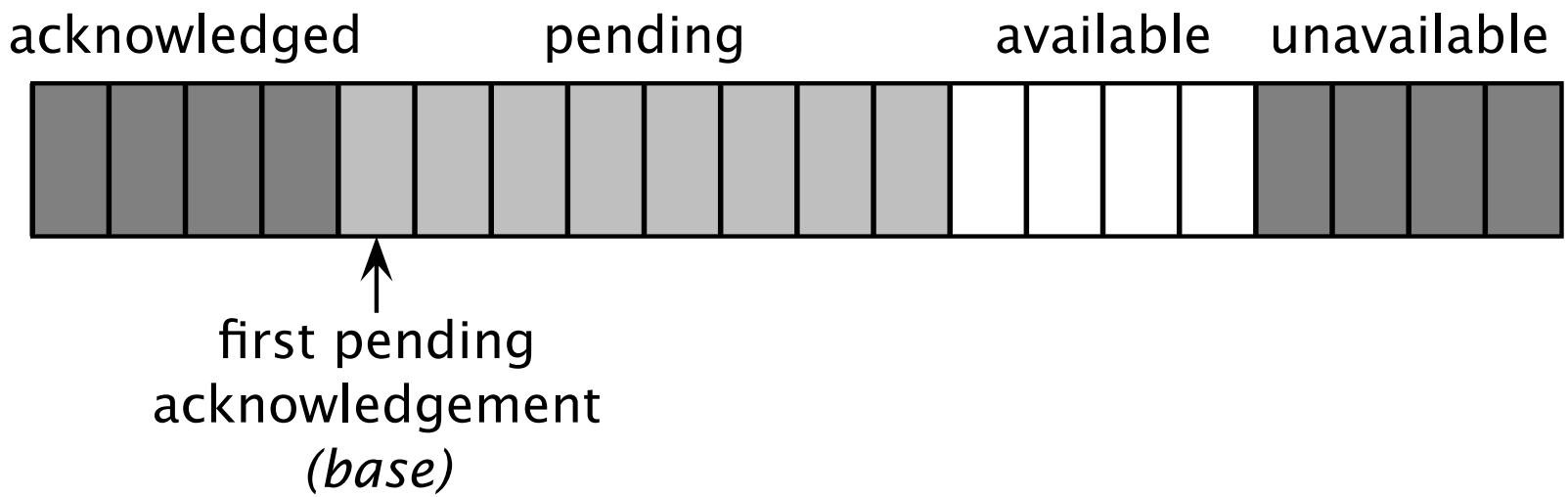
Go-Back-N

- **Idea:** the sender transmits multiple packets without waiting for an acknowledgement
- Sender has up to *W* unacknowledged packets in the pipeline
  - the sender's state machine gets very complex
  - we represent the sender's state with its queue of acknowledgements



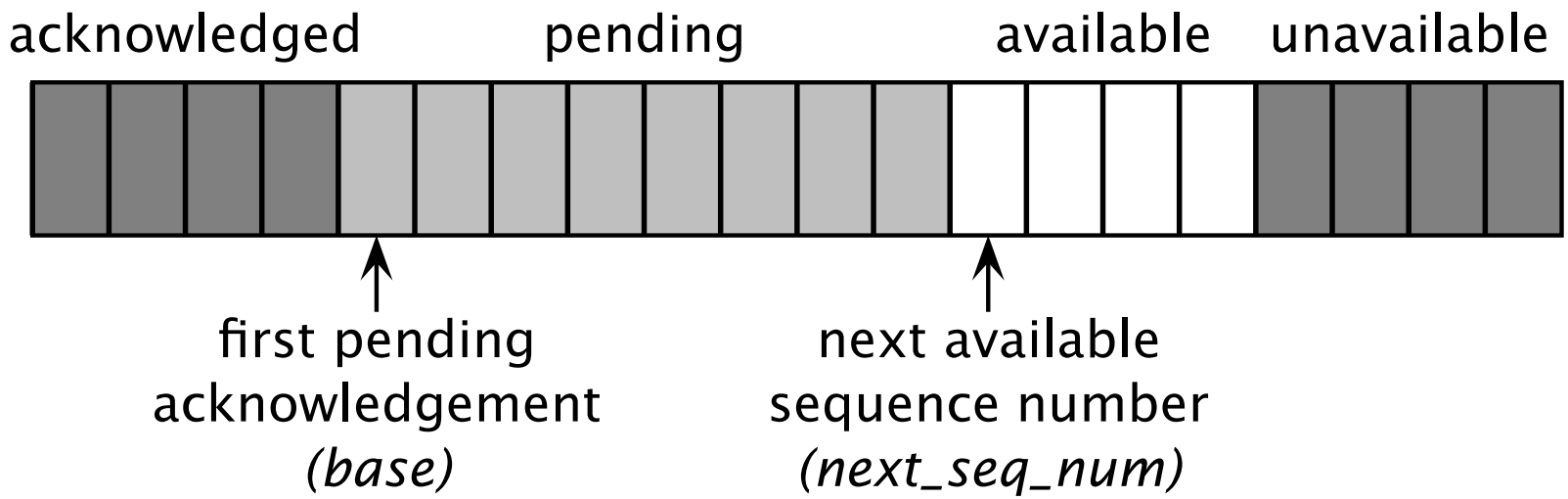
Go-Back-N

- **Idea:** the sender transmits multiple packets without waiting for an acknowledgement
- Sender has up to *W* unacknowledged packets in the pipeline
  - the sender's state machine gets very complex
  - we represent the sender's state with its queue of acknowledgements



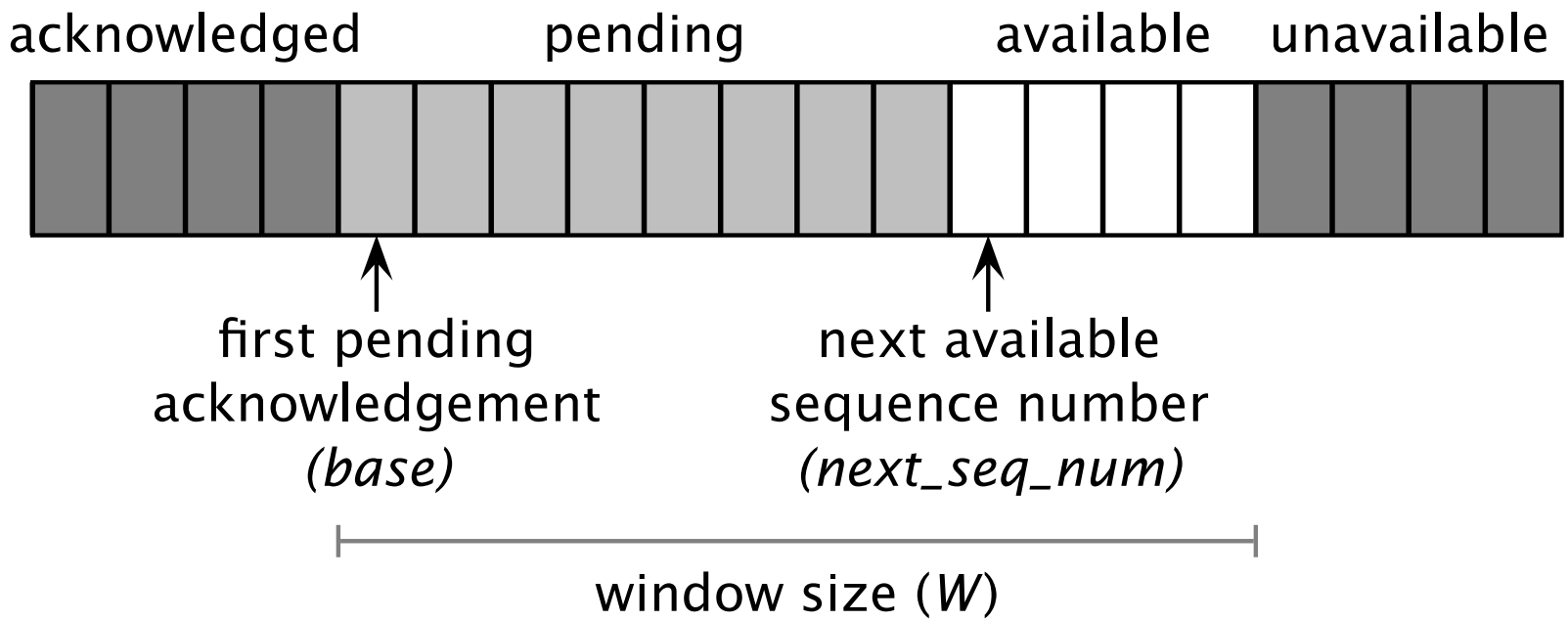
Go-Back-N

- **Idea:** the sender transmits multiple packets without waiting for an acknowledgement
- Sender has up to *W* unacknowledged packets in the pipeline
  - the sender's state machine gets very complex
  - we represent the sender's state with its queue of acknowledgements

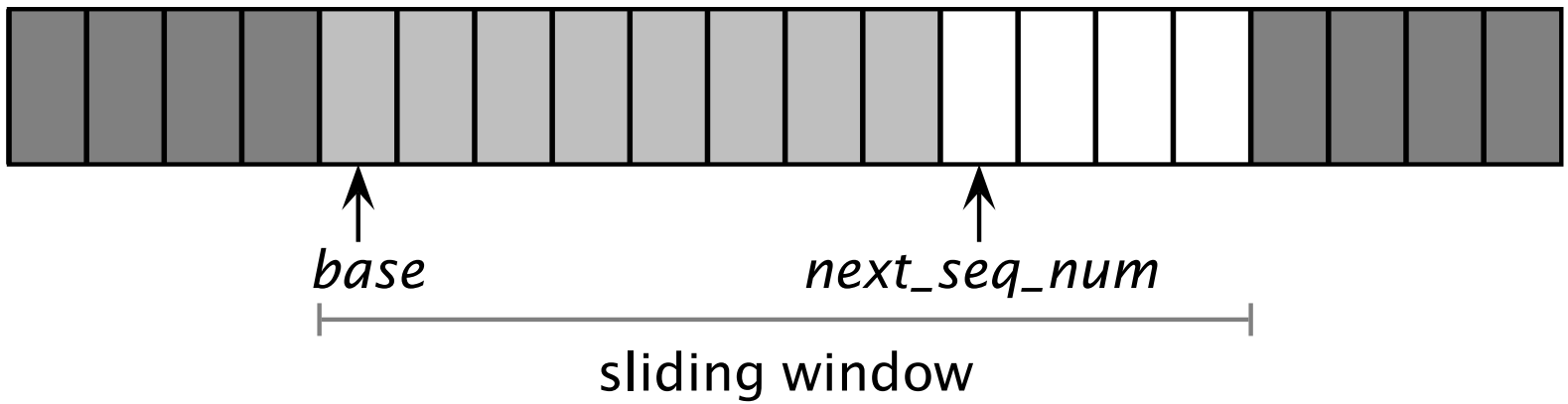


Go-Back-N

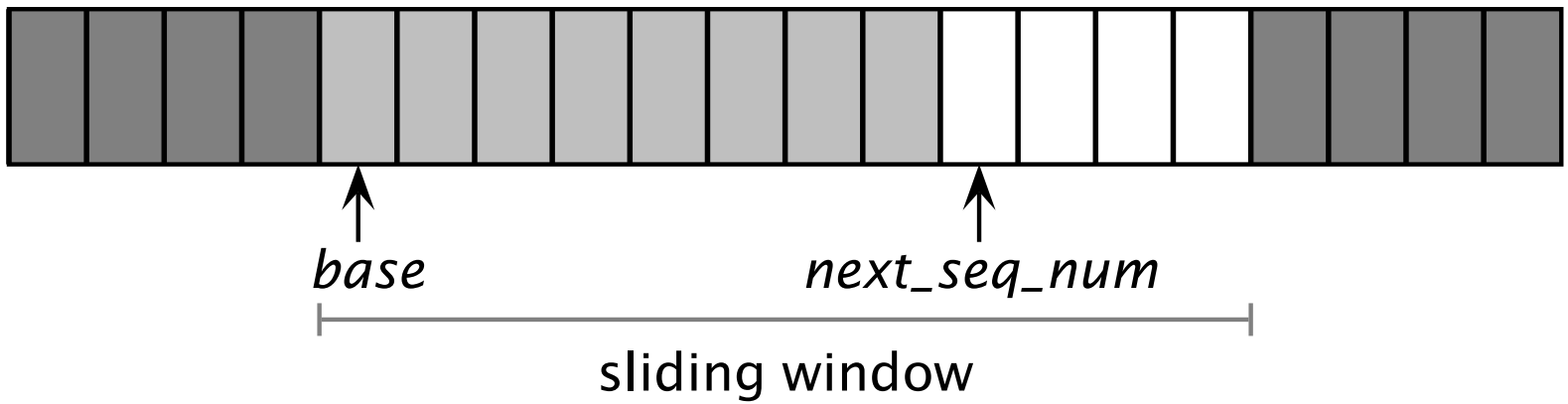
- **Idea:** the sender transmits multiple packets without waiting for an acknowledgement
- Sender has up to *W* unacknowledged packets in the pipeline
  - the sender's state machine gets very complex
  - we represent the sender's state with its queue of acknowledgements



Sliding Window Protocol: Sender

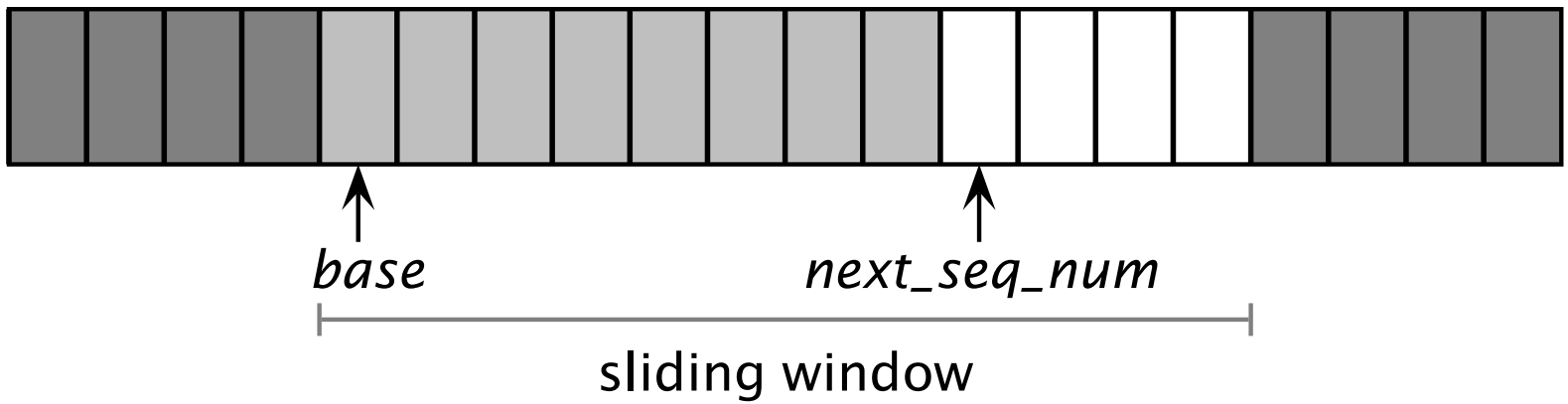


Sliding Window Protocol: Sender



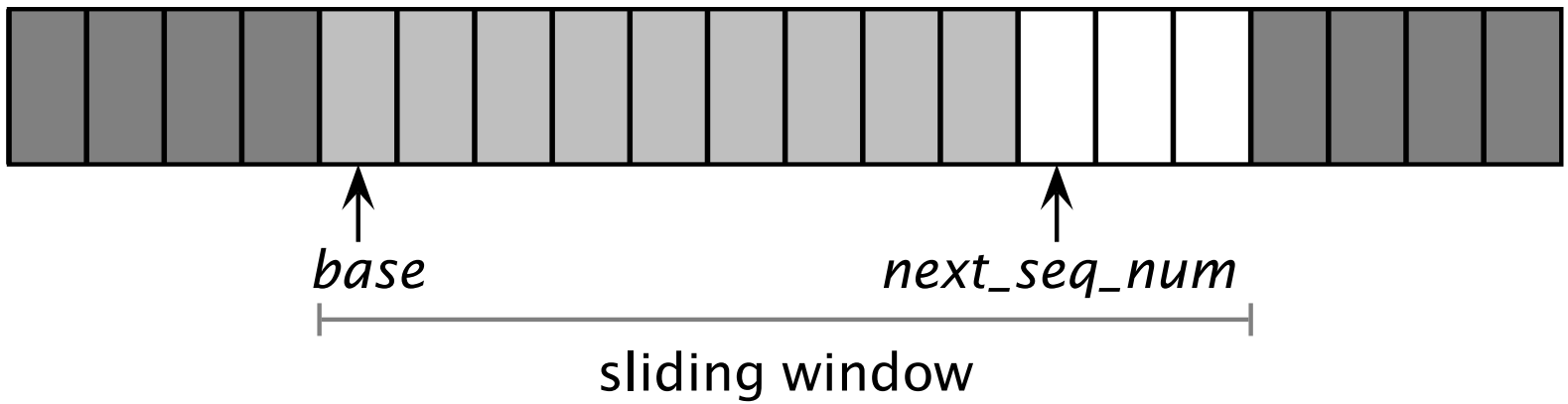
- r_send(pkt_1)

Sliding Window Protocol: Sender



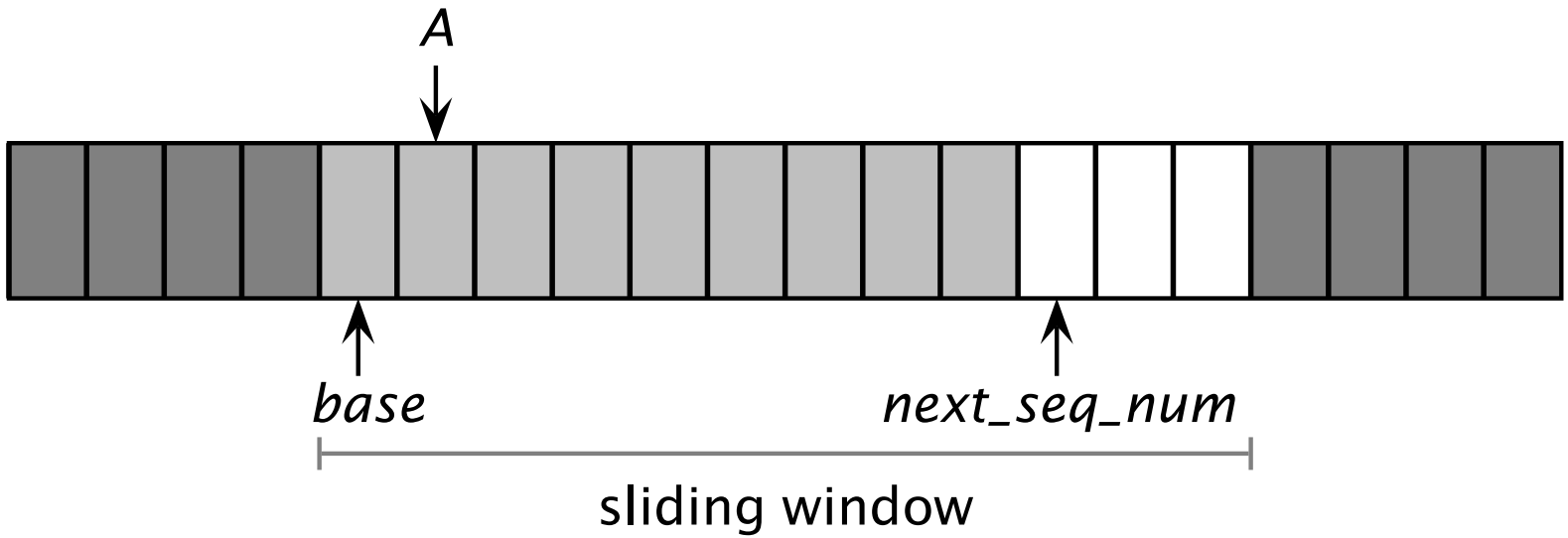
- r_send(pkt_1)
  - u_send([pkt_1,*next_seq_num*])

Sliding Window Protocol: Sender



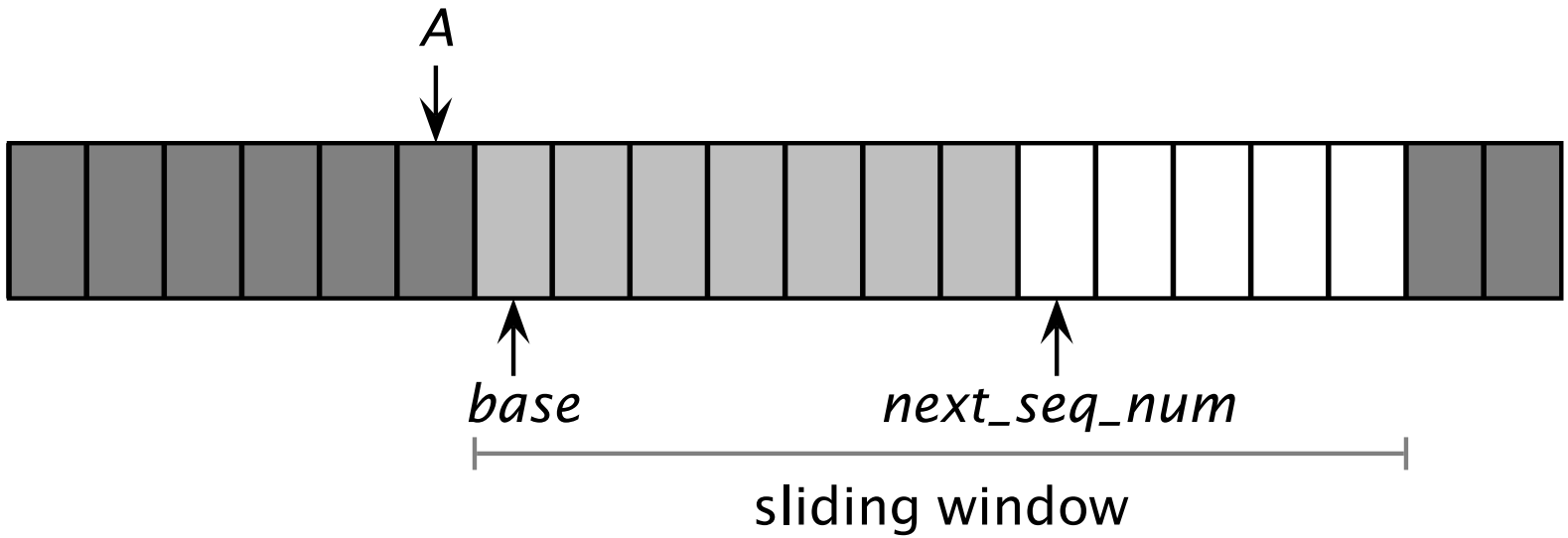
- r_send(pkt_1)
  - u_send([pkt_1,*next_seq_num*])
  - $next\_seq\_num = next\_seq\_num + 1$

Sliding Window Protocol: Sender



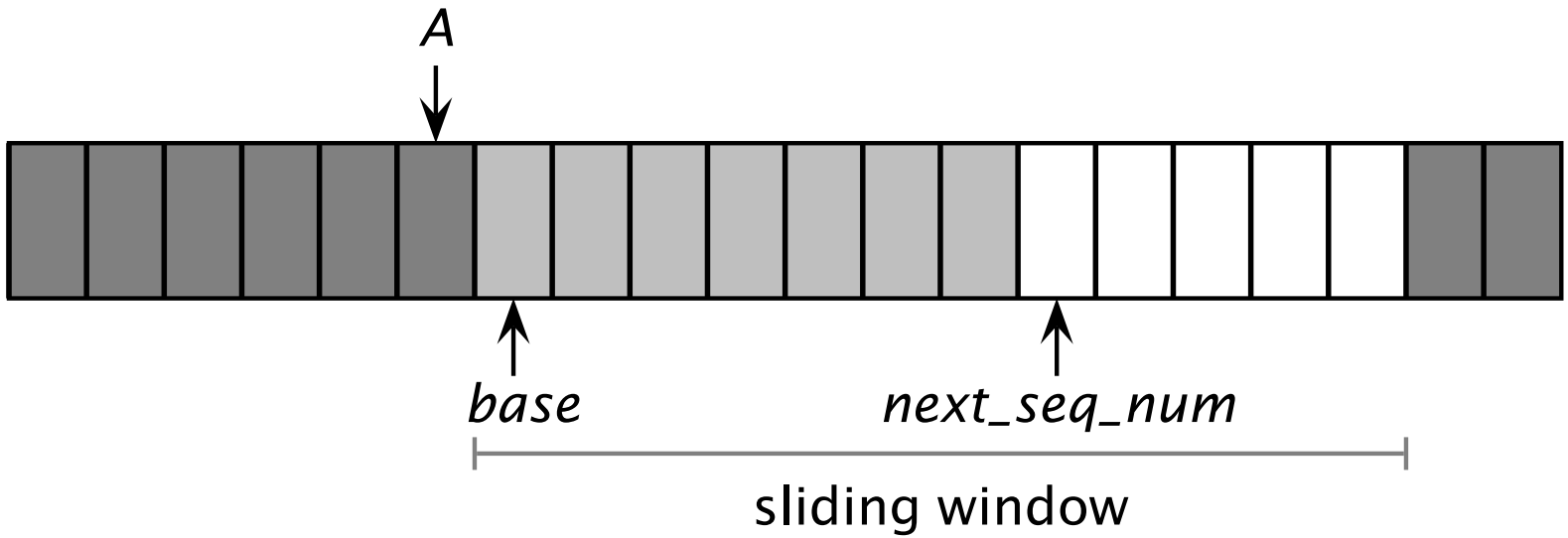
- r_send(pkt_1)
  - u_send([pkt_1,*next_seq_num*])
  - $next\_seq\_num = next\_seq\_num + 1$
- u_recv([ACK,*A*])

Sliding Window Protocol: Sender



- r_send(pkt_1)
  - u_send([pkt_1,*next_seq_num*])
  - $next\_seq\_num = next\_seq\_num + 1$
- u_recv([ACK,*A*])
  - $base = A + 1$

Sliding Window Protocol: Sender



- r_send(pkt_1)
  - u_send([pkt_1,*next_seq_num*])
  - $next\_seq\_num = next\_seq\_num + 1$
- u_recv([ACK,*A*])
  - $base = A + 1$
  - notice that acknewledgements are “cumulative”

Sliding Window Protocol: Sender

Sliding Window Protocol: Sender

- The sender remembers the first sequence number that has not yet been acknowledged
  - or the highest acknowledged sequence number
- The sender remembers the first available sequence number
  - or the highest used sequence number (i.e., sent to the receiver)
- The sender responds to three types of events

Sliding Window Protocol: Sender

- The sender remembers the first sequence number that has not yet been acknowledged
  - or the highest acknowledged sequence number
- The sender remembers the first available sequence number
  - or the highest used sequence number (i.e., sent to the receiver)
- The sender responds to three types of events
  - *r_send():* invocation from the application layer: send more data if a sequence number is available

Sliding Window Protocol: Sender

- The sender remembers the first sequence number that has not yet been acknowledged
  - or the highest acknowledged sequence number
- The sender remembers the first available sequence number
  - or the highest used sequence number (i.e., sent to the receiver)
- The sender responds to three types of events
  - *r_send():* invocation from the application layer: send more data if a sequence number is available
  - *ACK:* receipt of an acknowledgement: shift the window (it's a "cumulative" ACK)

Sliding Window Protocol: Sender

- The sender remembers the first sequence number that has not yet been acknowledged
  - or the highest acknowledged sequence number
- The sender remembers the first available sequence number
  - or the highest used sequence number (i.e., sent to the receiver)
- The sender responds to three types of events
  - *r_send():* invocation from the application layer: send more data if a sequence number is available
  - *ACK:* receipt of an acknowledgement: shift the window (it's a "cumulative" ACK)
  - *timeout:* "Go-Back-N." I.e., resend all the packets that have been sent but not acknowledged

Sliding Window Protocol: Sender

- *init*

  $base = 1$

  $next\_seq\_num = 1$

Sliding Window Protocol: Sender

- *init*

  $base = 1$

  $next\_seq\_num = 1$

- r_send(*data*)

```
if next_seq_num < base + W:
    pkt[next_seq_num] = [next_seq_num, data]*
    u_send(pkt[next_seq_num])
    if next_seq_num == base:
        start_timer()
    next_seq_num = next_seq_num + 1
else:
    refuse_data(data)      // block the sender
```

Sliding Window Protocol: Sender

- u_recv(*pkt*) **and** *pkt* is corrupted

Sliding Window Protocol: Sender

- u_recv(*pkt*) **and** *pkt* is corrupted

- u_recv(ACK,*ack_num*)

base = *ack_num* + 1 *// resume the sender*
if *next_seq_num* == *base*:
    stop_timer()
else:
    start_timer()

Sliding Window Protocol: Sender

- u_recv(*pkt*) **and** *pkt* is corrupted

- u_recv(ACK,*ack_num*)

```
base = ack_num + 1        // resume the sender
if next_seq_num == base:
    stop_timer()
else:
    start_timer()
```

- timeout

```
start_timer()
foreach i in base ... next_seq_num − 1:
    u_send(pkt[i])
```

Sliding Window Protocol: Receiver

Sliding Window Protocol: Receiver

- Simple: as in the stop-and-wait case, the receiver maintains a counter representing the *expected sequence number*

Sliding Window Protocol: Receiver

- Simple: as in the stop-and-wait case, the receiver maintains a counter representing the *expected sequence number*
- The receiver waits for a (good) data packet with the expected sequence number

Sliding Window Protocol: Receiver

- Simple: as in the stop-and-wait case, the receiver maintains a counter representing the *expected sequence number*
- The receiver waits for a (good) data packet with the expected sequence number
  - acknowledges the expected sequence number

Sliding Window Protocol: Receiver

- Simple: as in the stop-and-wait case, the receiver maintains a counter representing the *expected sequence number*
- The receiver waits for a (good) data packet with the expected sequence number
  - acknowledges the expected sequence number
  - delivers the data to the application

Sliding Window Protocol: Receiver

- *init*

  $expected\_seq\_num = 1$

  $ackpkt = [ACK, 0]^*$

Sliding Window Protocol: Receiver

- *init*

  $expected\_seq\_num = 1$

  $ackpkt = [ACK, 0]^*$

- u_recv([*data*, *seq_num*]) **and** good
  and $seq\_num = expected\_seq\_num$

  ---

  r_recv(*data*)

  $ackpkt = [ACK, expected\_seq\_num]^*$

  $expected\_seq\_num = expected\_seq\_num + 1$

  u_send(*ackpkt*)

Sliding Window Protocol: Receiver

- *init*

  $expected\_seq\_num = 1$

  $ackpkt = [ACK, 0]^*$

- u_recv([*data*, *seq_num*]) **and** good
  and $seq\_num = expected\_seq\_num$

  ---

  r_recv(*data*)

  $ackpkt = [ACK, expected\_seq\_num]^*$

  $expected\_seq\_num = expected\_seq\_num + 1$

  u_send(*ackpkt*)

- u_recv([*data*, *seq_num*])
  and (corrupted **or** $seq\_num \neq expected\_seq\_num$)

  ---

  u_send(*ackpkt*)

Comments

- Concepts

Comments

- Concepts
  - *sequence numbers*

Comments

- Concepts
  - *sequence numbers*
  - *sliding window*

Comments

- Concepts
  - *sequence numbers*
  - *sliding window*
  - *cumulative acknowledgements*

Comments

- Concepts
  - *sequence numbers*
  - *sliding window*
  - *cumulative acknowledgements*
  - *checksums*, *timeouts*, and *sender-initiated retransmission*

Comments

- Concepts
  - *sequence numbers*
  - *sliding window*
  - *cumulative acknowledgements*
  - *checksums*, *timeouts*, and *sender-initiated retransmission*
- Advantages: *simple*

Comments

- Concepts
  - *sequence numbers*
  - *sliding window*
  - *cumulative acknowledgements*
  - *checksums*, *timeouts*, and *sender-initiated retransmission*
- Advantages: *simple*
  - the sender maintains *two counters* and a *one timer*
  - the receiver maintains *one counter*

Comments

- Concepts
  - *sequence numbers*
  - *sliding window*
  - *cumulative acknowledgements*
  - *checksums*, *timeouts*, and *sender-initiated retransmission*
- Advantages: *simple*
  - the sender maintains *two counters* and a *one timer*
  - the receiver maintains *one counter*
- Disadvantages: *not optimal*, *not adaptive*

Comments

- Concepts
  - *sequence numbers*
  - *sliding window*
  - *cumulative acknowledgements*
  - *checksums*, *timeouts*, and *sender-initiated retransmission*
- Advantages: *simple*
  - the sender maintains *two counters* and a *one timer*
  - the receiver maintains *one counter*
- Disadvantages: *not optimal*, *not adaptive*
  - the sender can fill the window without filling the pipeline

Comments

- Concepts
  - *sequence numbers*
  - *sliding window*
  - *cumulative acknowledgements*
  - *checksums*, *timeouts*, and *sender-initiated retransmission*
- Advantages: *simple*
  - the sender maintains *two counters* and a *one timer*
  - the receiver maintains *one counter*
- Disadvantages: *not optimal*, *not adaptive*
  - the sender can fill the window without filling the pipeline
  - the receiver may buffer out-of-order packets...

Performance Analysis

- What is a good value for W?

Performance Analysis

- What is a good value for W?
  - W that achieves the *maximum utilization* of the connection

Performance Analysis

- What is a good value for W?
  - W that achieves the *maximum utilization* of the connection

$$\begin{aligned} \ell &= stream \\ d &= 500ms \\ R &= 1Mb/s \\ W &= ? \end{aligned}$$

Performance Analysis

- What is a good value for W?
  - W that achieves the *maximum utilization* of the connection

$$\begin{aligned} \ell &= stream \\ d &= 500ms \\ R &= 1Mb/s \\ W &= ? \end{aligned}$$

- The problem may seem a bit underspecified. What is the (average) packet size?

$$\begin{aligned} \ell_{pkt} &= 1Kb \\ d &= 500ms \\ R &= 1Mb/s \\ W &= \frac{2d \times R}{\ell_{pkt}} = 1000 \end{aligned}$$

Performance Analysis

- The RTT–throughput product ($2d \times R$) is the crucial factor

Performance Analysis

- The RTT–throughput product ($2d \times R$) is the crucial factor
  - $W \times \ell_{pkt} \leq 2d \times R$
    - why $W \times \ell_{pkt} > 2d \times R$ doesn't make much sense?

Performance Analysis

- The RTT–throughput product ($2d \times R$) is the crucial factor
  - $W \times \ell_{pkt} \leq 2d \times R$
    - why $W \times \ell_{pkt} > 2d \times R$ doesn't make much sense?
  - maximum channel utilization when $W \times \ell_{pkt} = 2d \times R$
  - $2d \times R$ can be thought of as the *capacity* of a connection

Problems with Go-Back-N

- Let's consider a fully utilized connection

Problems with Go-Back-N

- Let's consider a fully utilized connection

$$\begin{aligned} \ell_{pkt} &= 1Kb \\ d &= 500ms \\ R &= 1Mb/s \\ W &= \frac{R \times d}{\ell_{pkt}} = 1000 \end{aligned}$$

Problems with Go-Back-N

- Let's consider a fully utilized connection

$$\begin{aligned} \ell_{pkt} &= 1Kb \\ d &= 500ms \\ R &= 1Mb/s \\ W &= \frac{R \times d}{\ell_{pkt}} = 1000 \end{aligned}$$

- What happens if the first packet (or acknowledgement) is lost?

Problems with Go-Back-N

- Let's consider a fully utilized connection

$$\begin{aligned} \ell_{pkt} &= 1Kb \\ d &= 500ms \\ R &= 1Mb/s \\ W &= \frac{R \times d}{\ell_{pkt}} = 1000 \end{aligned}$$

- What happens if the first packet (or acknowledgement) is lost?
- Sender retransmits the entire content of its buffers

Problems with Go-Back-N

- Let's consider a fully utilized connection

$$\begin{aligned} \ell_{pkt} &= 1Kb \\ d &= 500ms \\ R &= 1Mb/s \\ W &= \frac{R \times d}{\ell_{pkt}} = 1000 \end{aligned}$$

- What happens if the first packet (or acknowledgement) is lost?
- Sender retransmits the entire content of its buffers
  - $W \times \ell_{pkt} = 2d \times R = 1Mb$
  - retransmitting 1Mb to recover 1Kb worth of data isn't exactly the best solution. Not to mention conjestions...

Problems with Go-Back-N

- Let's consider a fully utilized connection

$$\begin{aligned} \ell_{pkt} &= 1Kb \\ d &= 500ms \\ R &= 1Mb/s \\ W &= \frac{R \times d}{\ell_{pkt}} = 1000 \end{aligned}$$

- What happens if the first packet (or acknowledgement) is lost?
- Sender retransmits the entire content of its buffers
  - $W \times \ell_{pkt} = 2d \times R = 1Mb$
  - retransmitting 1Mb to recover 1Kb worth of data isn't exactly the best solution. Not to mention conjestions...
- Is there a better way to deal with retransmissions?

Selective Repeat

- **Idea:** have the sender retransmit only those packets that it suspects were lost or corrupted

Selective Repeat

- **Idea:** have the sender retransmit only those packets that it suspects were lost or corrupted
  - sender maintains a vector of acknowledgement flags

Selective Repeat

- **Idea:** have the sender retransmit only those packets that it suspects were lost or corrupted
  - sender maintains a vector of acknowledgement flags
  - receiver maintains a vector of acknowledged falgs

Selective Repeat

- **Idea:** have the sender retransmit only those packets that it suspects were lost or corrupted
  - sender maintains a vector of acknowledgement flags
  - receiver maintains a vector of acknowledged falgs
  - in fact, receiver maintains a buffer of out-of-order packets

Selective Repeat

- **Idea:** have the sender retransmit only those packets that it suspects were lost or corrupted
  - sender maintains a vector of acknowledgement flags
  - receiver maintains a vector of acknowledged falgs
  - in fact, receiver maintains a buffer of out-of-order packets
  - sender maintains a timer for each pending packet

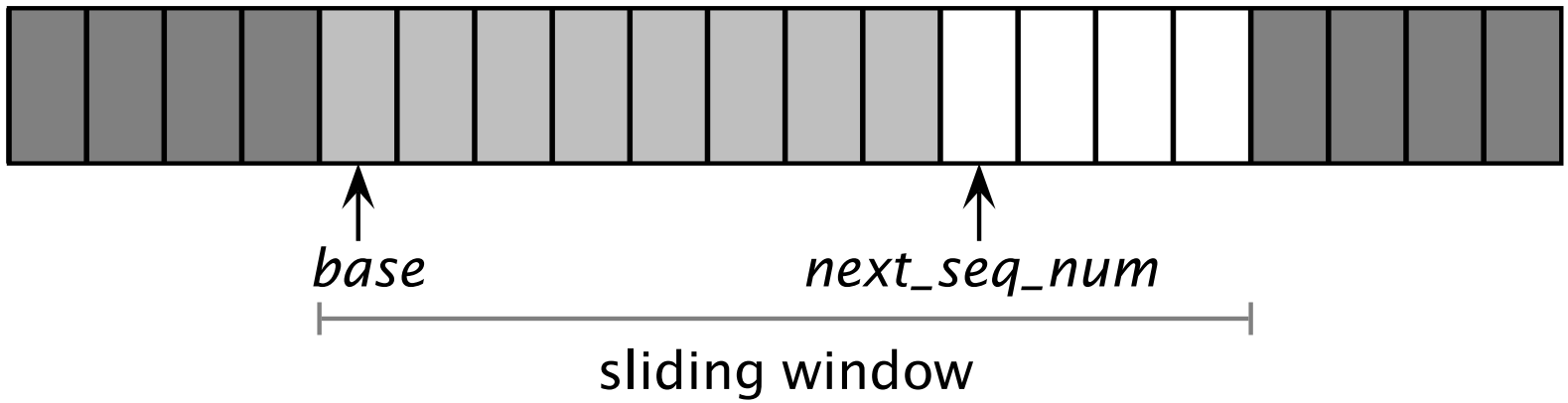
Selective Repeat

- **Idea:** have the sender retransmit only those packets that it suspects were lost or corrupted
  - sender maintains a vector of acknowledgement flags
  - receiver maintains a vector of acknowledged falgs
  - in fact, receiver maintains a buffer of out-of-order packets
  - sender maintains a timer for each pending packet
  - sender resends a packet when its timer expires

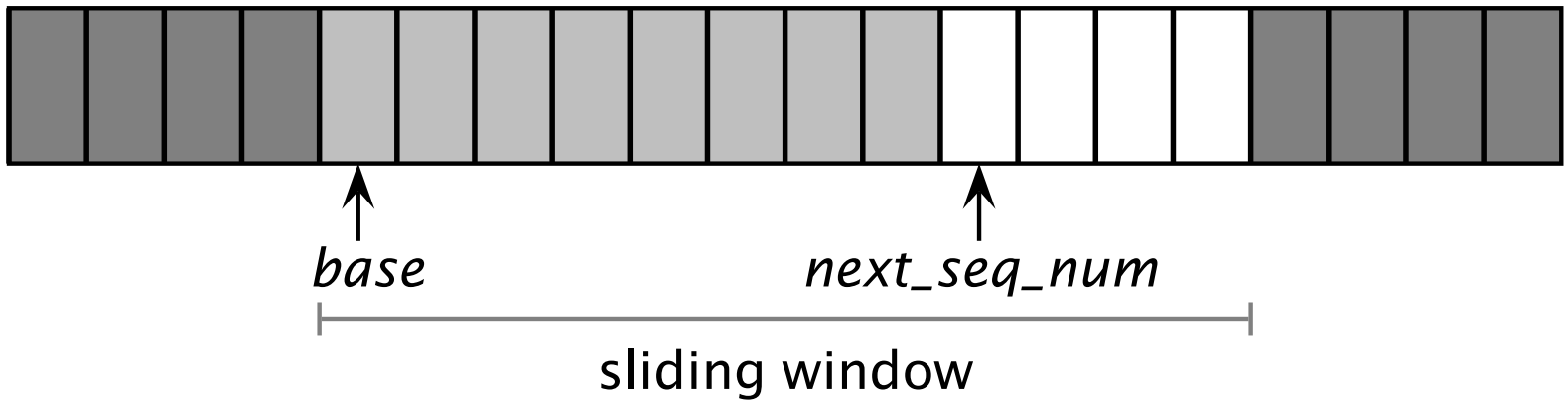
Selective Repeat

- **Idea:** have the sender retransmit only those packets that it suspects were lost or corrupted
  - sender maintains a vector of acknowledgement flags
  - receiver maintains a vector of acknowledged falgs
  - in fact, receiver maintains a buffer of out-of-order packets
  - sender maintains a timer for each pending packet
  - sender resends a packet when its timer expires
  - sender slides the window when the lowest pending sequence number is acknowledged

Selective Repeat: Sender

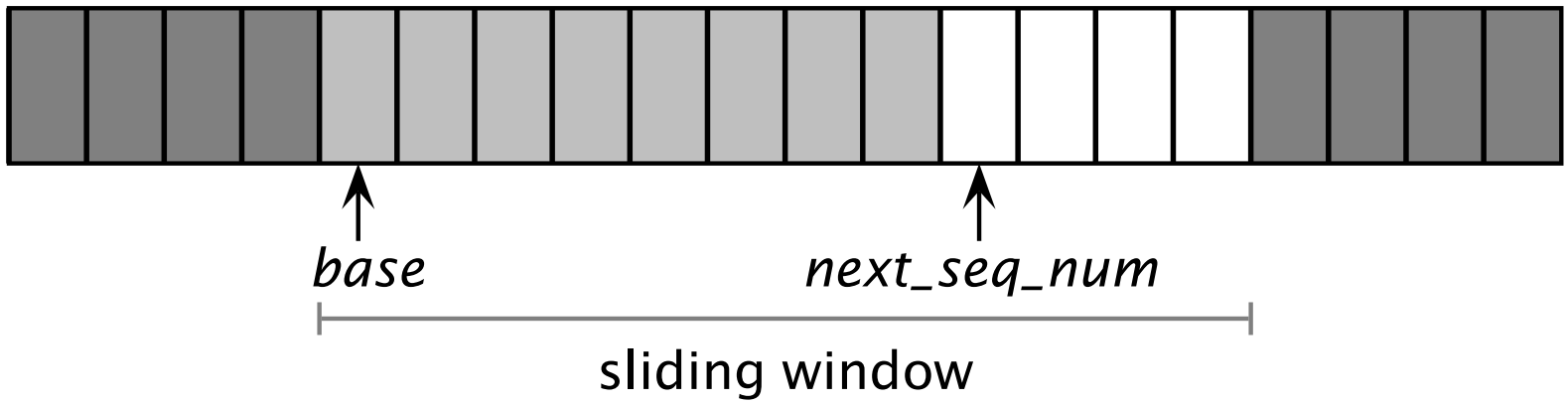


Selective Repeat: Sender



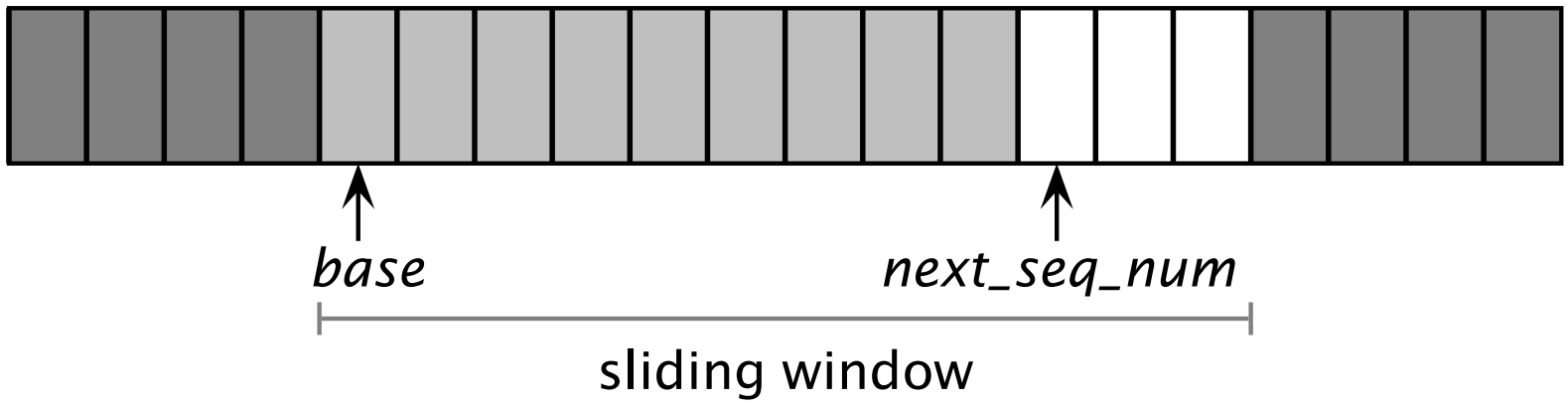
- r_send(pkt_1)

Selective Repeat: Sender



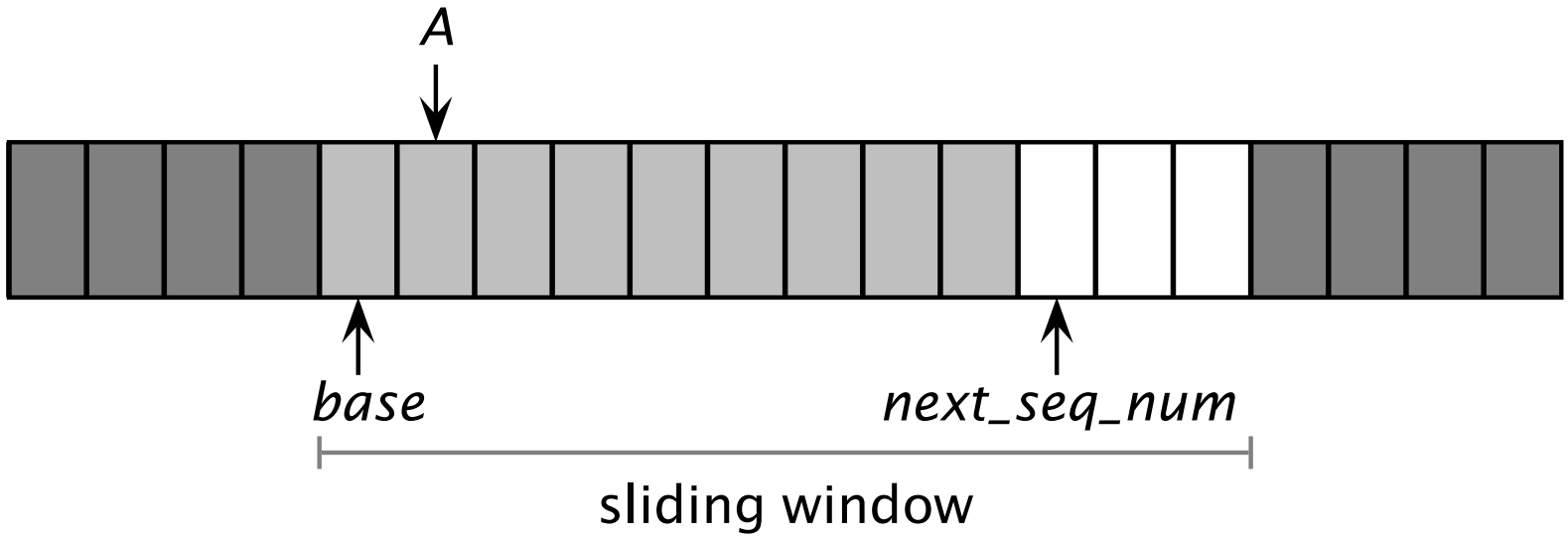
- r_send(pkt_1)
  - u_send([pkt_1,*next_seq_num*])
  - start_timer(*next_seq_num*)

Selective Repeat: Sender



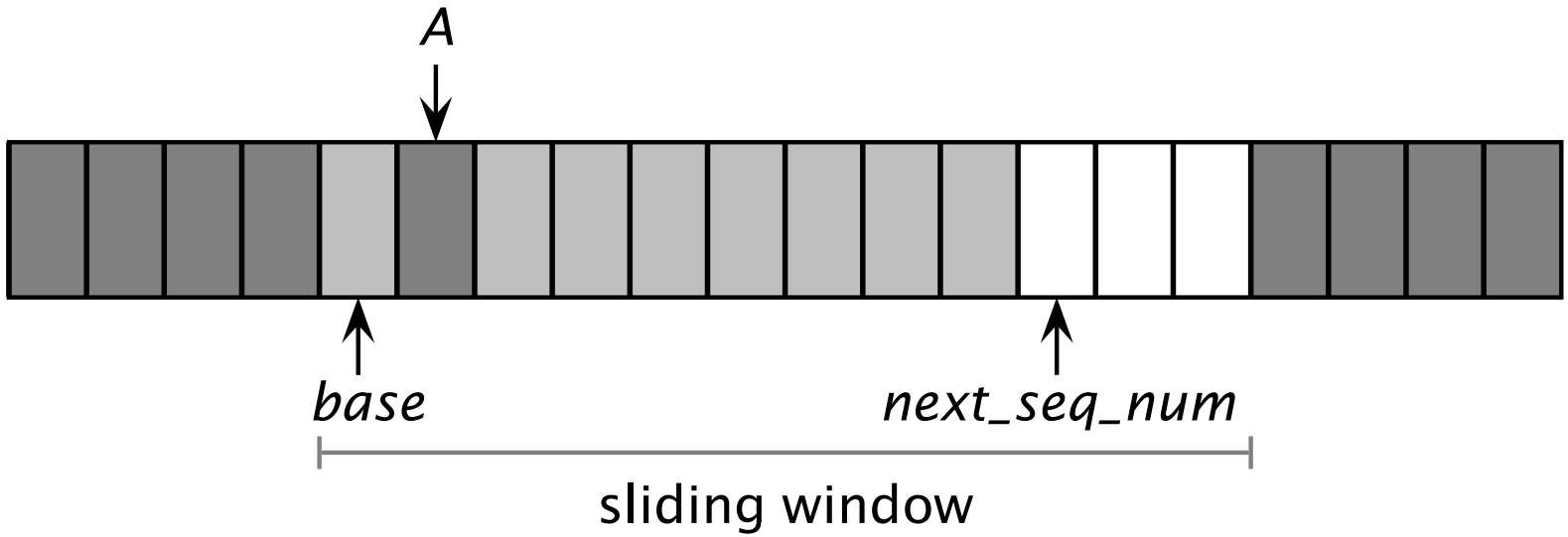
- r_send(pkt_1)
  - u_send([pkt_1,*next_seq_num*])
  - start_timer(*next_seq_num*)
  - $next\_seq\_num = next\_seq\_num + 1$

Selective Repeat: Sender



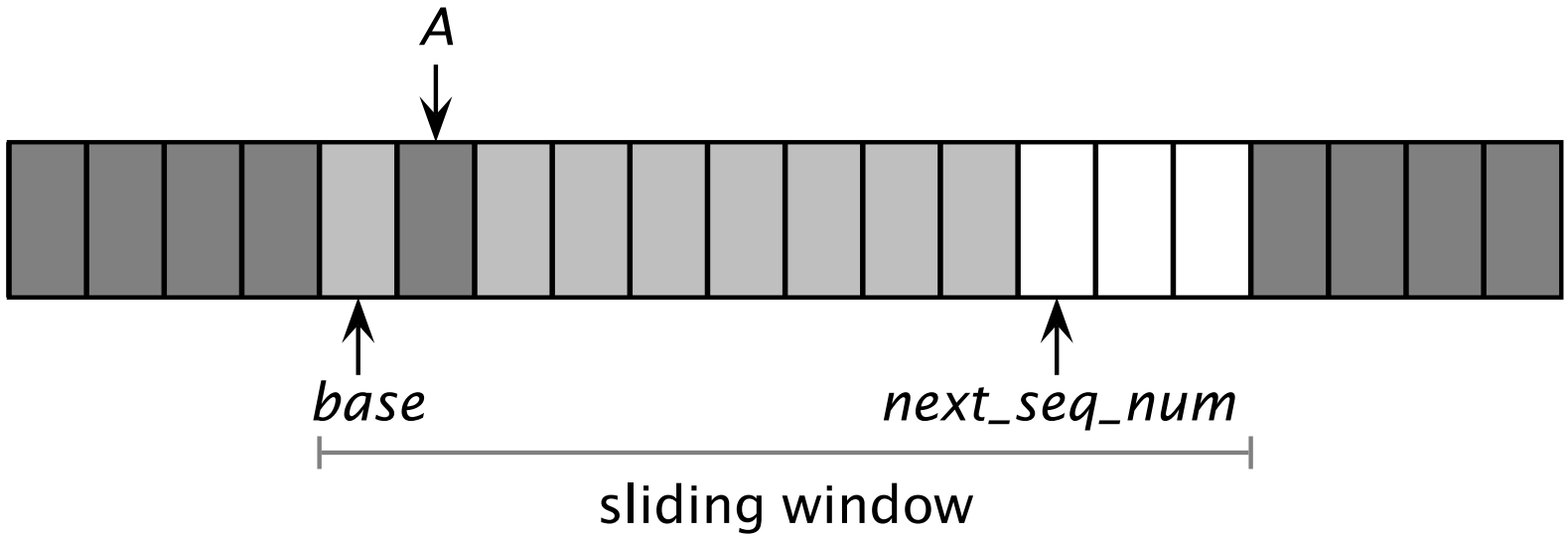
- r_send(pkt_1)
  - u_send([pkt_1,*next_seq_num*])
  - start_timer(*next_seq_num*)
  - $next\_seq\_num = next\_seq\_num + 1$
- u_recv([ACK,*A*])

Selective Repeat: Sender



- r_send(pkt_1)
  - u_send([pkt_1,*next_seq_num*])
  - start_timer(*next_seq_num*)
  - $next\_seq\_num = next\_seq\_num + 1$
- u_recv([ACK,*A*])
  - $acks[A] = 1$ // *remember that A was ACK'd*

Selective Repeat: Sender

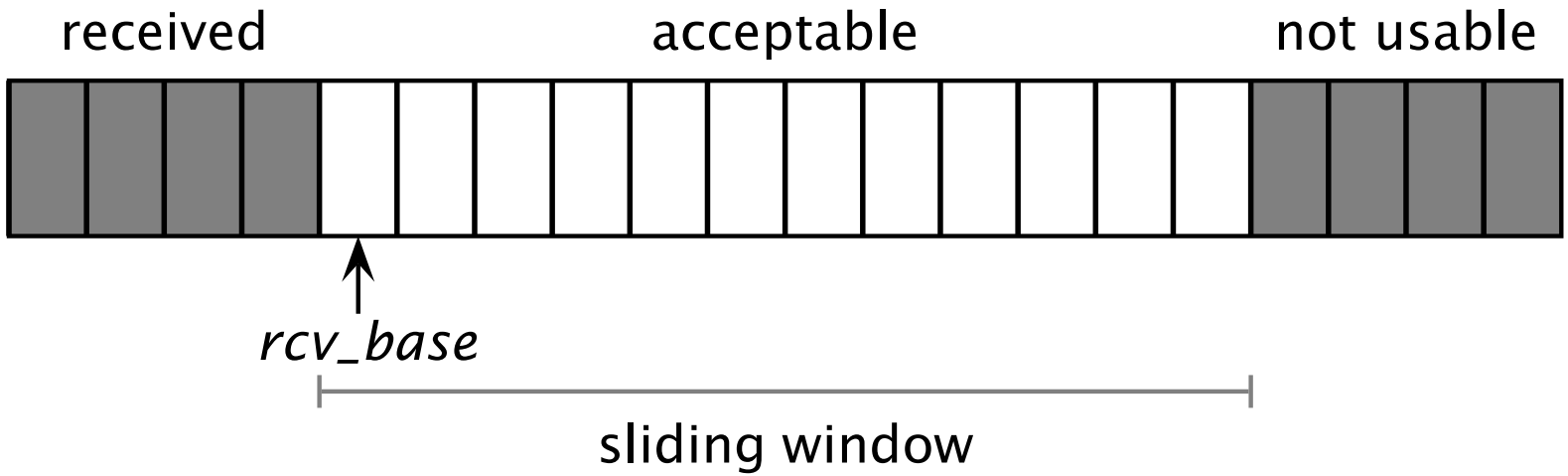


- r_send(pkt_1)
  - u_send([pkt_1,*next_seq_num*])
  - start_timer(*next_seq_num*)
  - *next_seq_num* = *next_seq_num* + 1

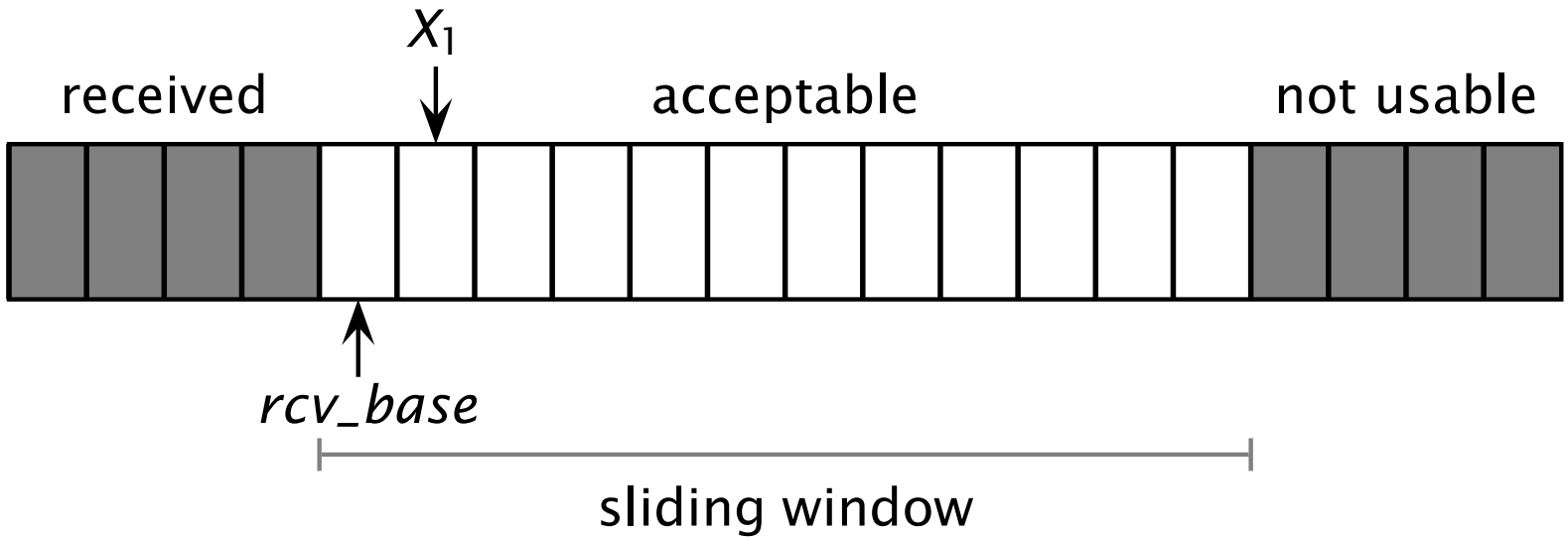
- u_recv([ACK,*A*])
  - *acks*[*A*] = 1 // *remember that A was ACK'd*
  - acknewledgements are no longer "cumulative"

Selective Repeat: Receiver

Selective Repeat: Receiver

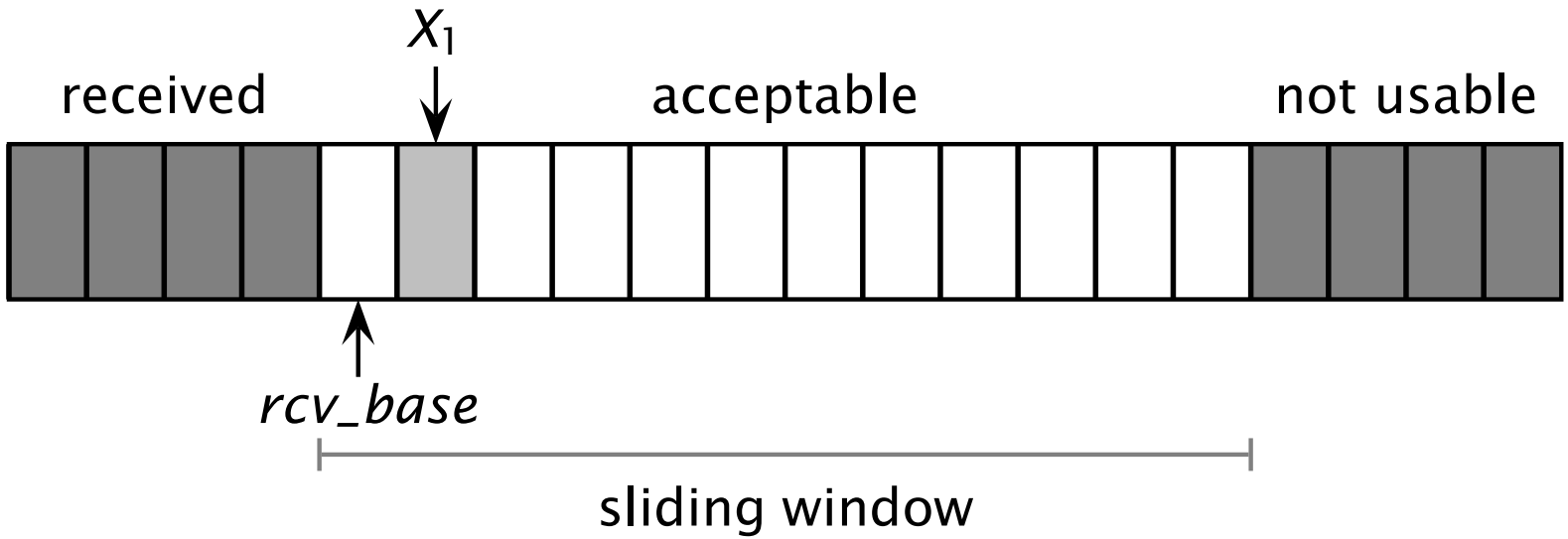


Selective Repeat: Receiver



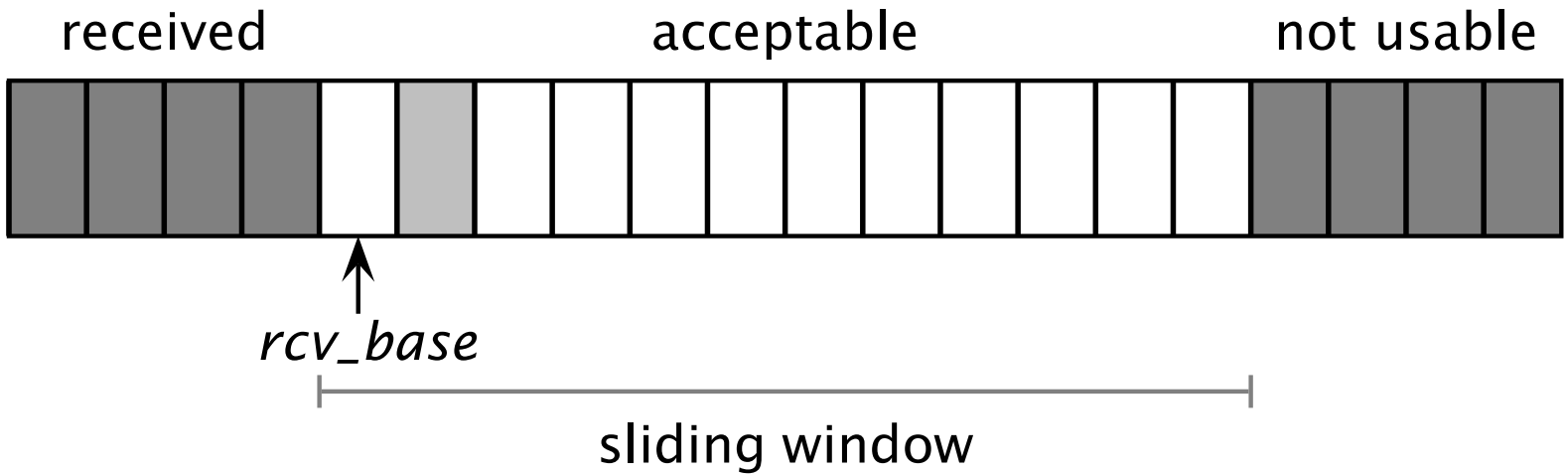
- u_recv([pkt_1,X_1]) **and** $rcv\_base \leq X_1 < rcv\_base + W$

Selective Repeat: Receiver

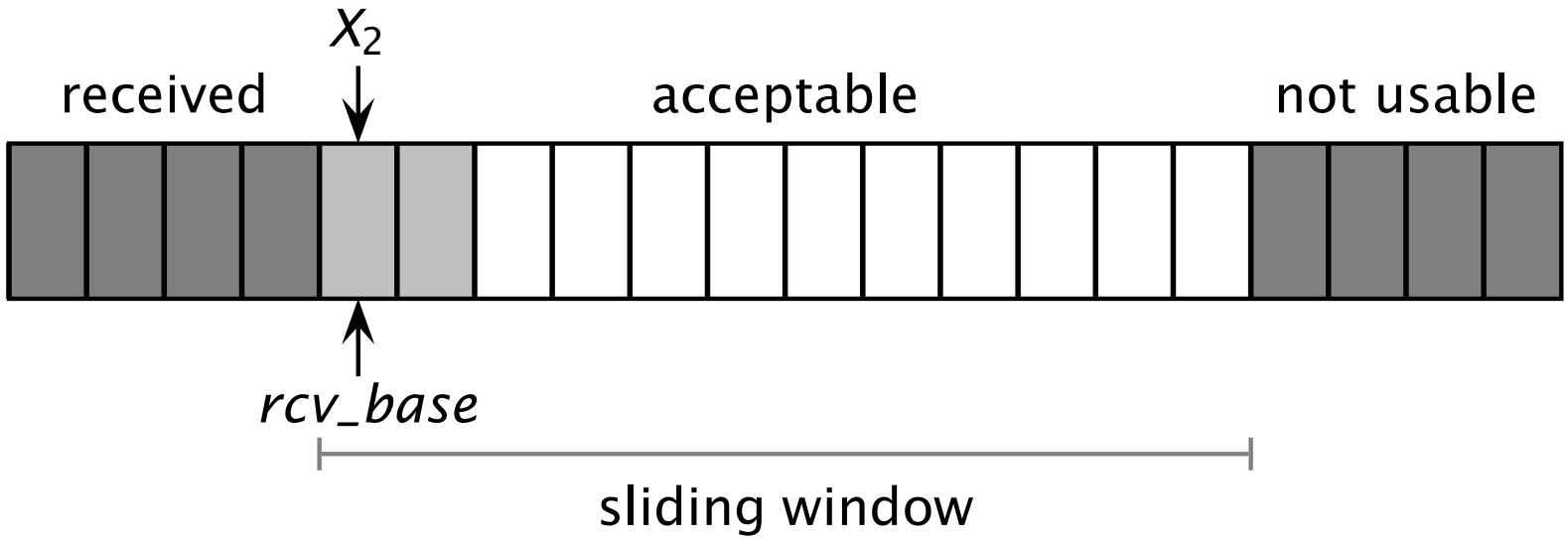


- u_recv([pkt_1,X_1]) **and** $rcv\_base \leq X_1 < rcv\_base + W$
  - $buffer[X_1] = pkt_1$
  - u_send([ACK, X_1]*) *// no longer a "cumulative" ACK*

Selective Repeat: Receiver

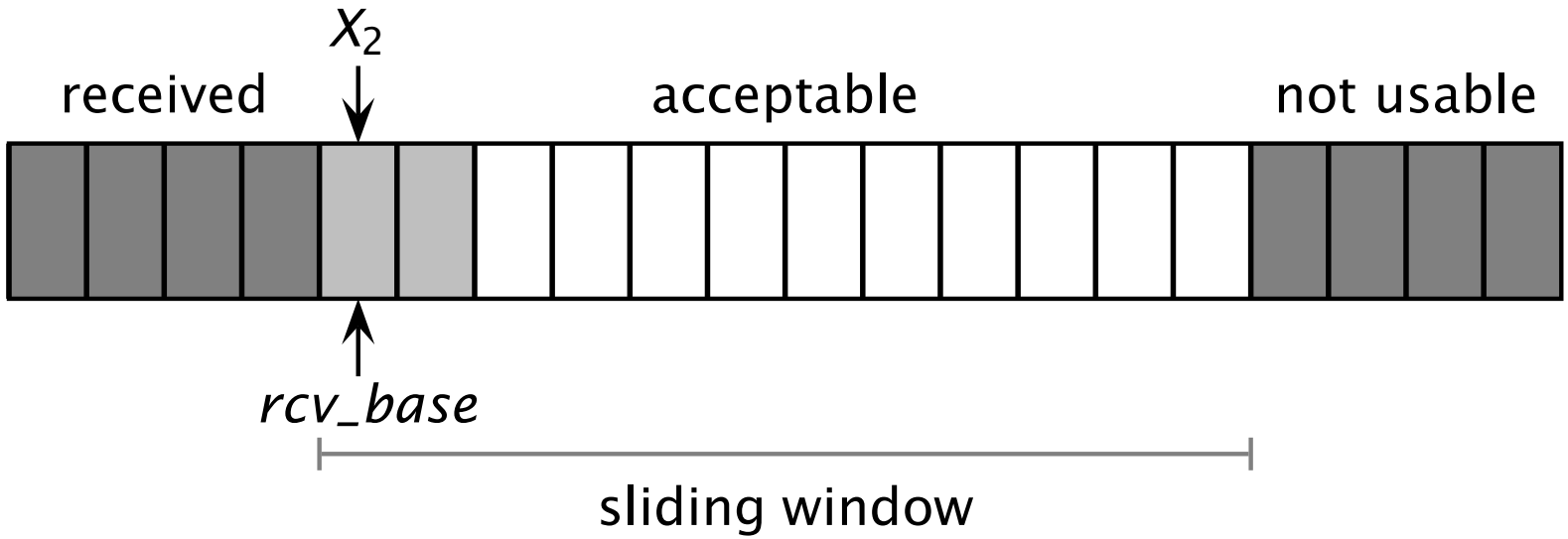


Selective Repeat: Receiver



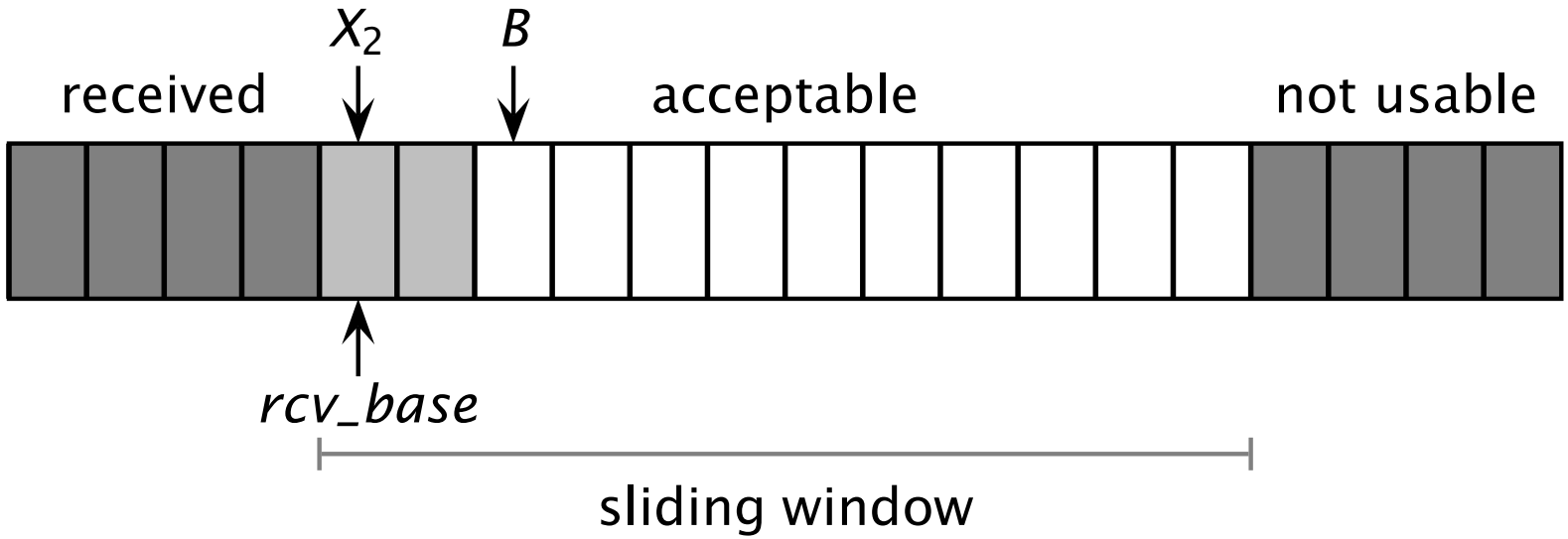
- u_recv([pkt_2,X_2]) **and** $rcv\_base \leq X_2 < rcv\_base + W$
  - $buffer[X_2] = pkt_2$
  - u_send([ACK, X_2]*)

Selective Repeat: Receiver



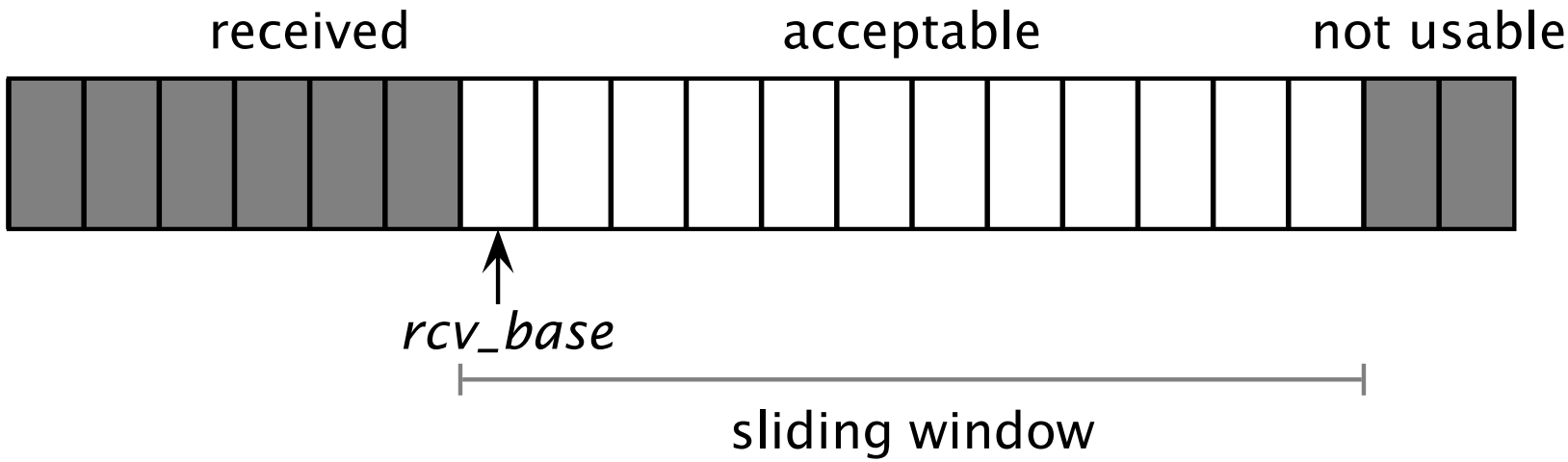
- u_recv([pkt_2,X_2]) **and** $rcv\_base \leq X_2 < rcv\_base + W$
  - $buffer[X_2] = pkt_2$
  - u_send([ACK, X_2]*)
  - **if** X_2 == rcv_base:

Selective Repeat: Receiver



- u_recv([pkt_2,X_2]) **and** $rcv\_base \leq X_2 < rcv\_base + W$
  - $buffer[X_2] = pkt_2$
  - u_send([ACK, X_2]*)
  - **if** X_2 == rcv_base:
    $B = first\_missing\_seq\_num()$
    foreach i **in** $rcv\_base \ldots B-1$:
    r_recv($buffer[i]$)

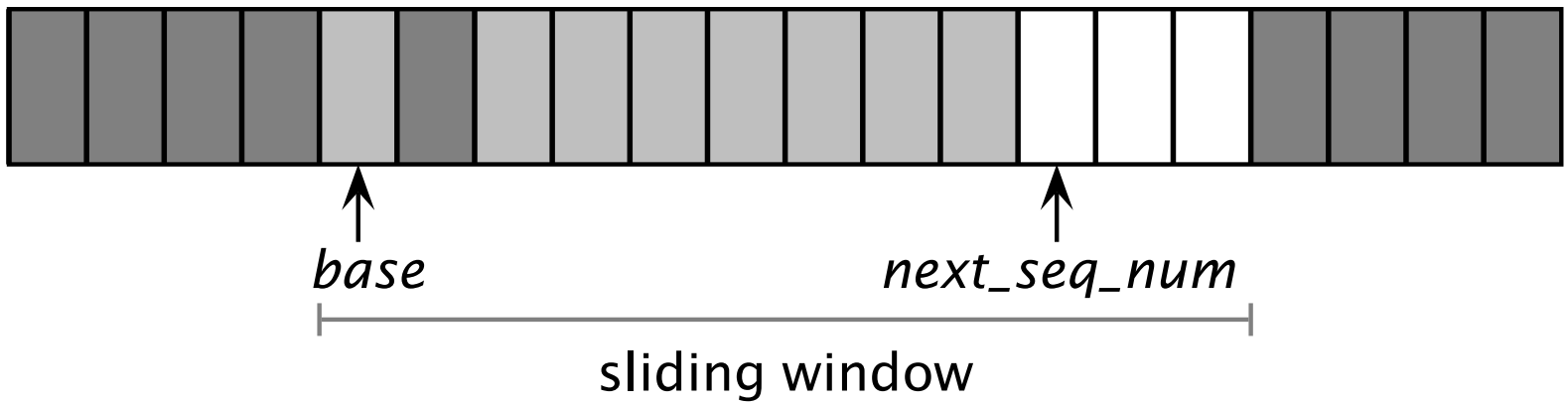
Selective Repeat: Receiver



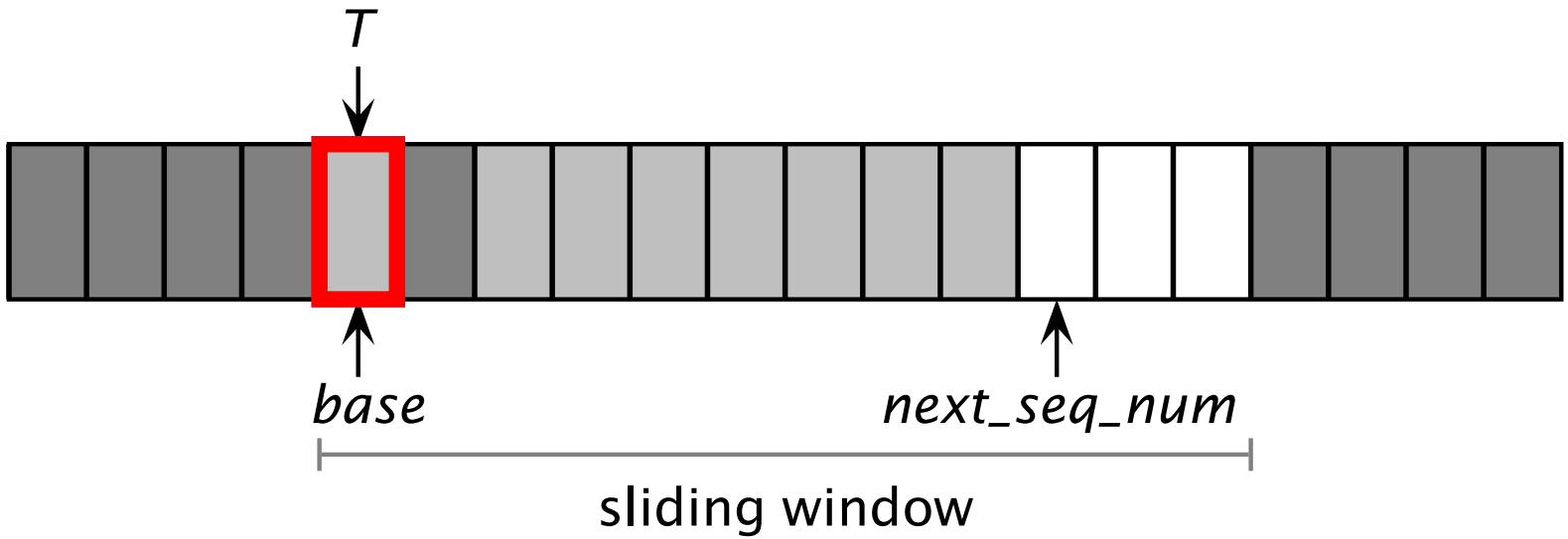
- u_recv([pkt_2,X_2]) **and** $rcv\_base \leq X_2 < rcv\_base + W$
  - $buffer[X_2] = pkt_2$
  - u_send([ACK, X_2]*)
  - **if** X_2 == rcv_base:
    $B = first\_missing\_seq\_num()$
    foreach i **in** $rcv\_base \ldots B-1$:
    r_recv($buffer[i]$)
    $rcv\_base = B$

Selective Repeat: Sender

Selective Repeat: Sender

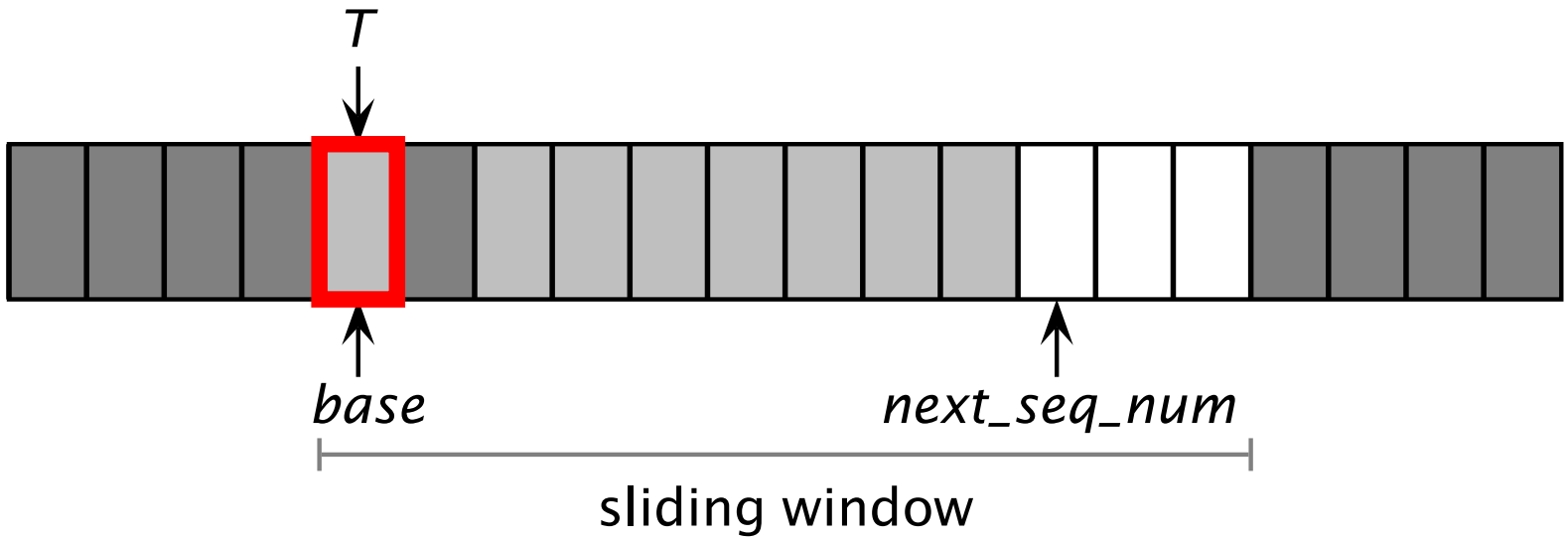


Selective Repeat: Sender



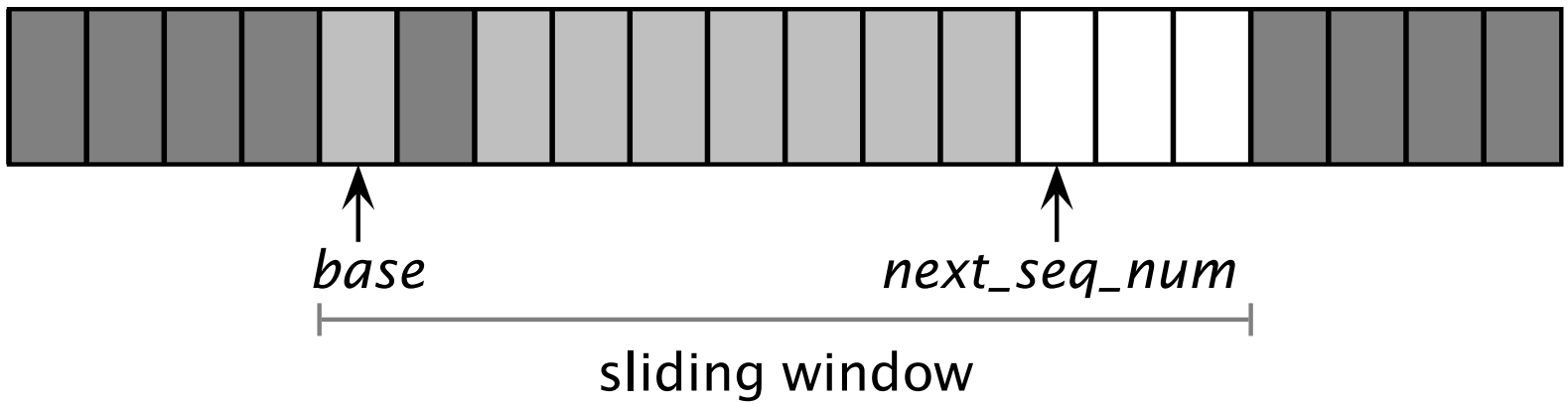
- Timeout for sequence number *T*

Selective Repeat: Sender

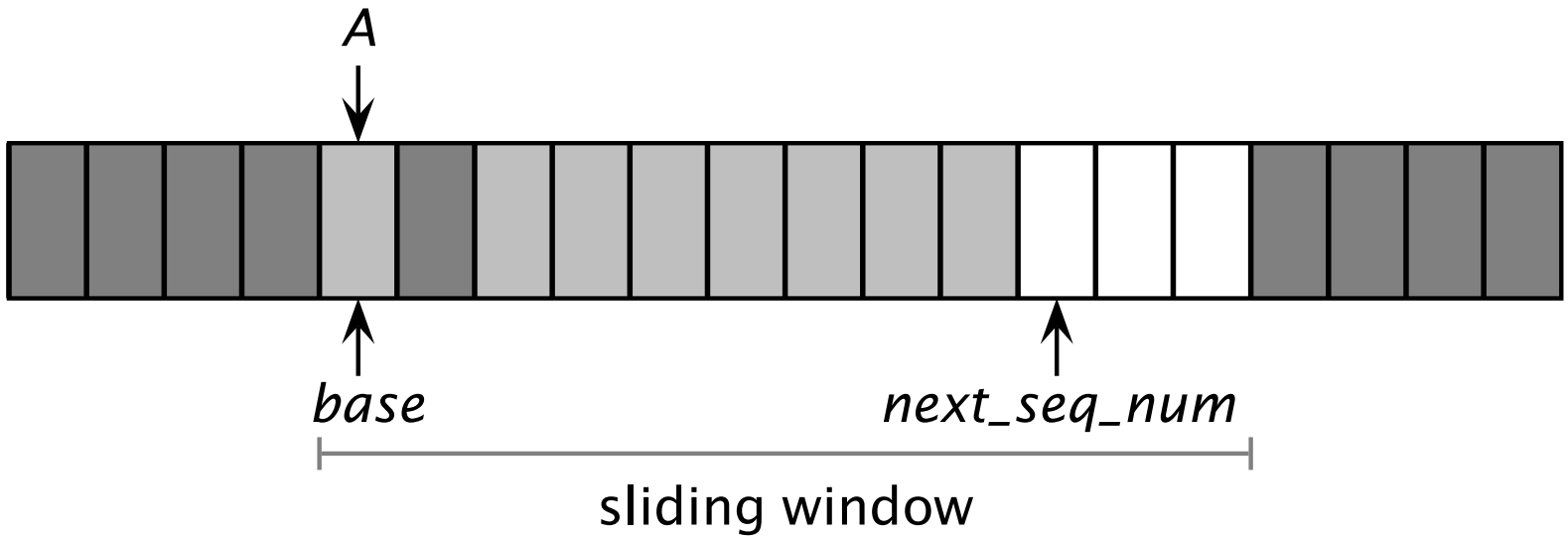


- Timeout for sequence number T
  - u_send($[pkt[T], T]^*$)

Selective Repeat: Sender

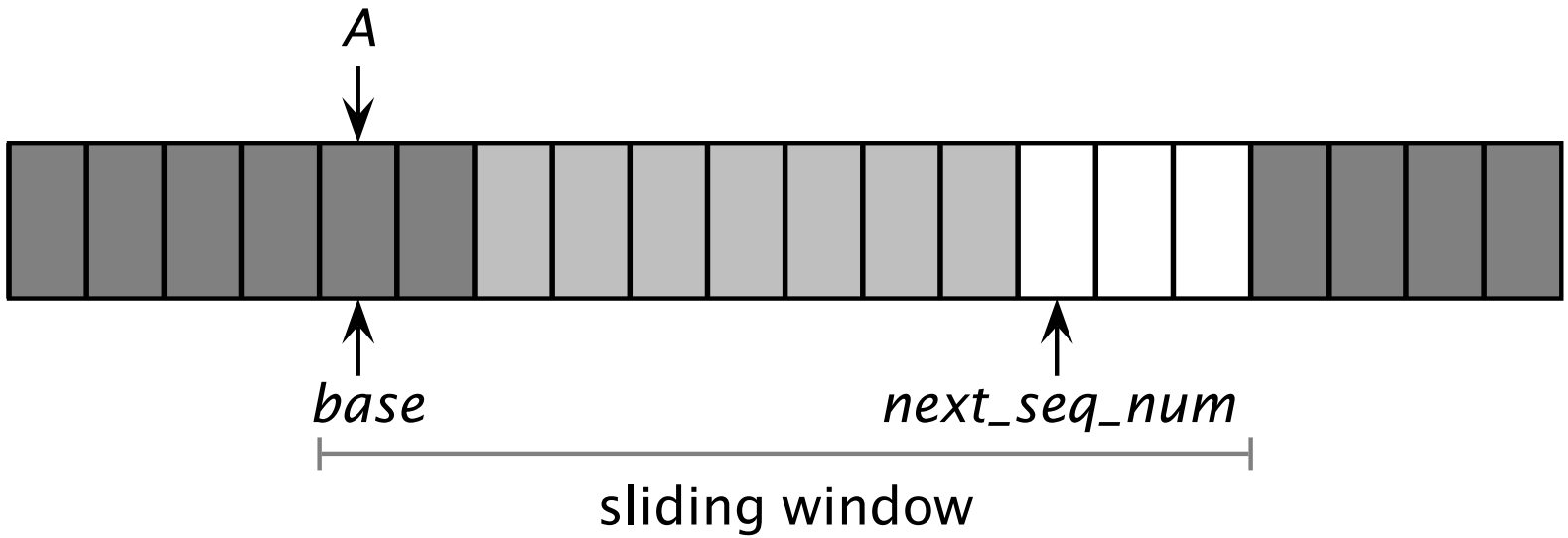


Selective Repeat: Sender



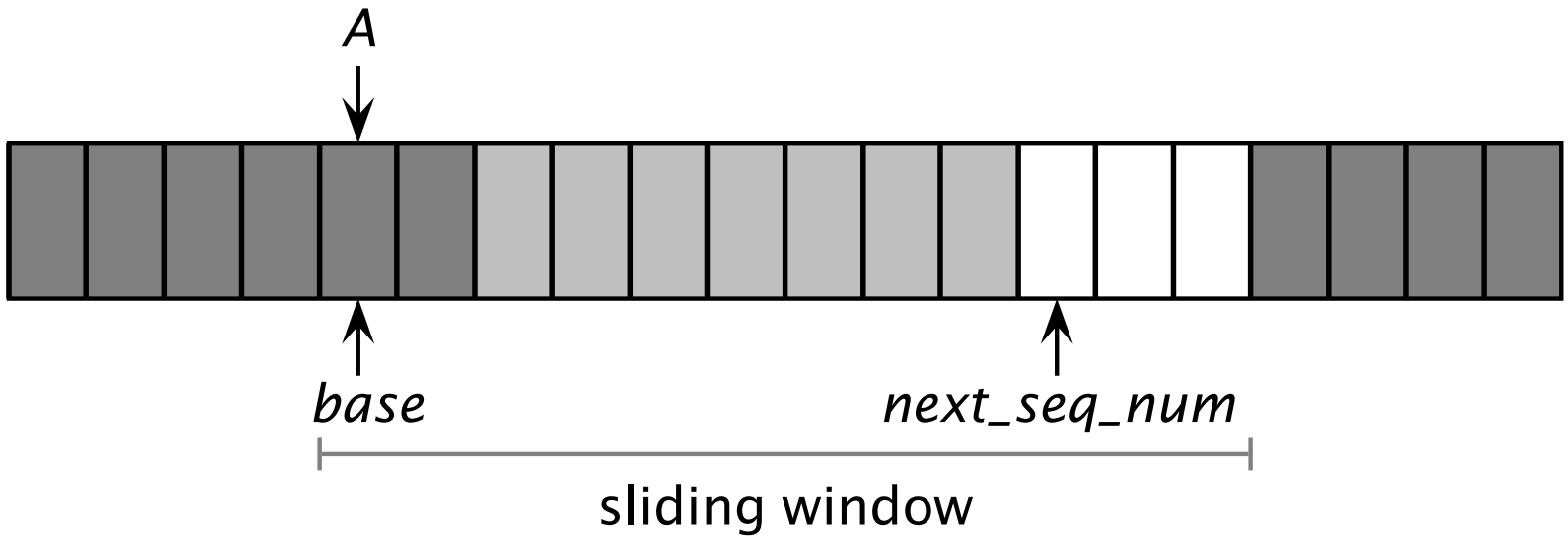
- u_recv([ACK,*A*])

Selective Repeat: Sender



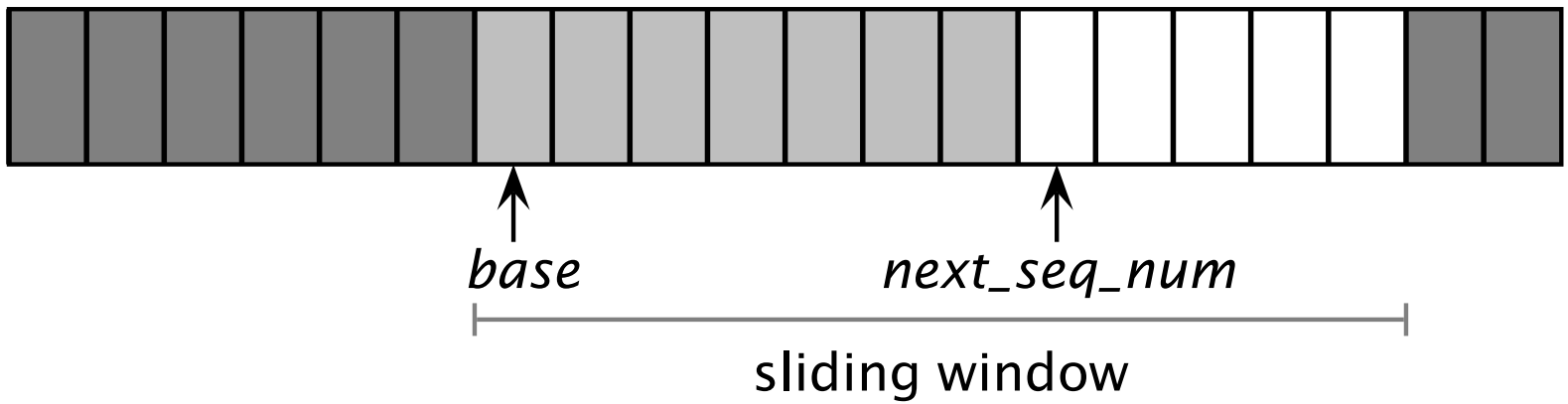
- u_recv([ACK,*A*])
  - $acks[A] = 1$

Selective Repeat: Sender



- u_recv([ACK,*A*])
  - $acks[A] = 1$
  - **if** *A* == *base*:

Selective Repeat: Sender



- u_recv([ACK,*A*])
  - $acks[A] = 1$
  - **if** *A* == *base*:
    base = *first_missing_ack_num*()