# Telecomunicazioni

## Roberto Verdone

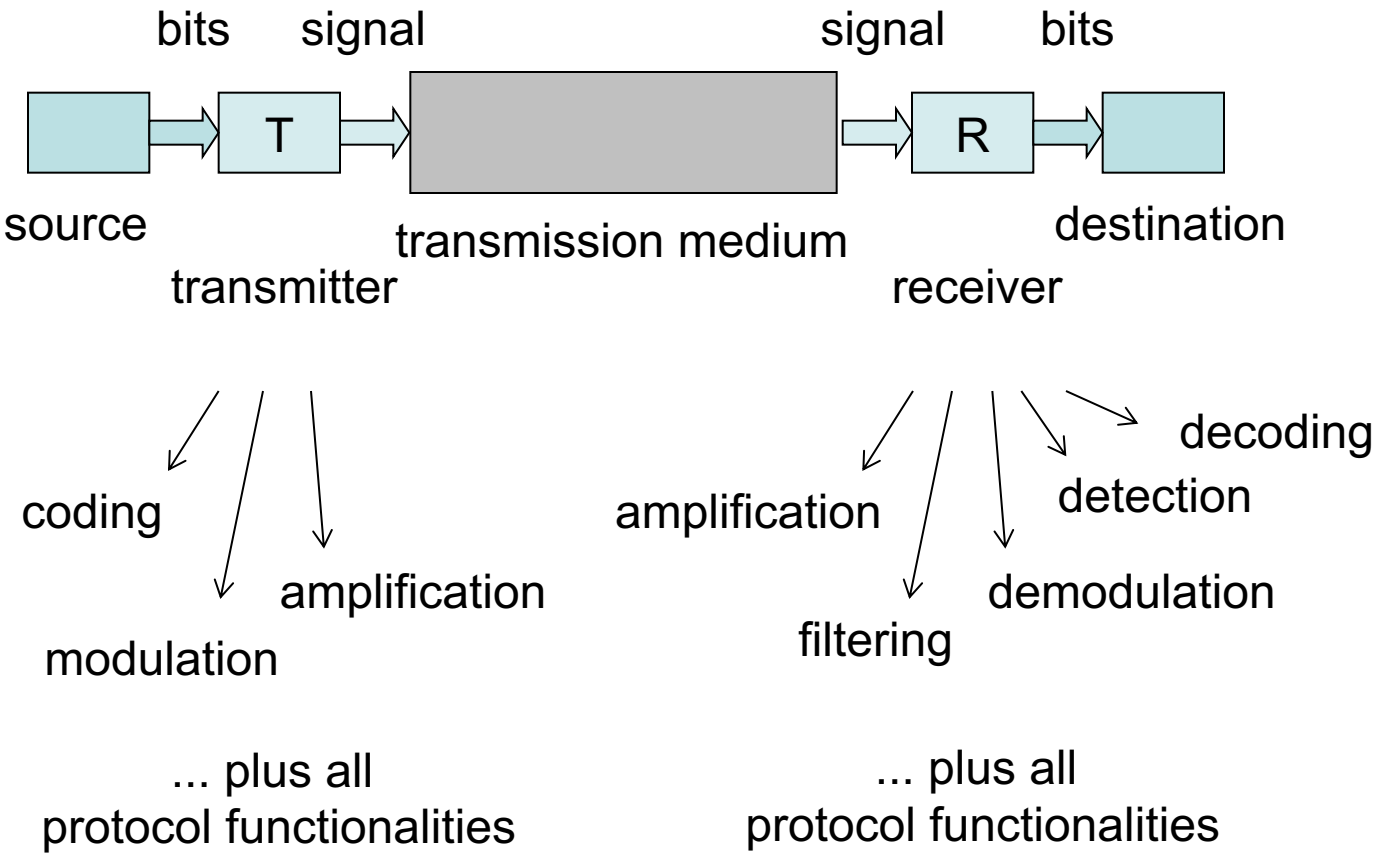
roberto.verdone@unibo.it
www.robertoverdone.org
https://www.linkedin.com/in/roberto-verdone/

Radio Networks
DEI, University of Bologna

# Fundamentals of Digital Comms

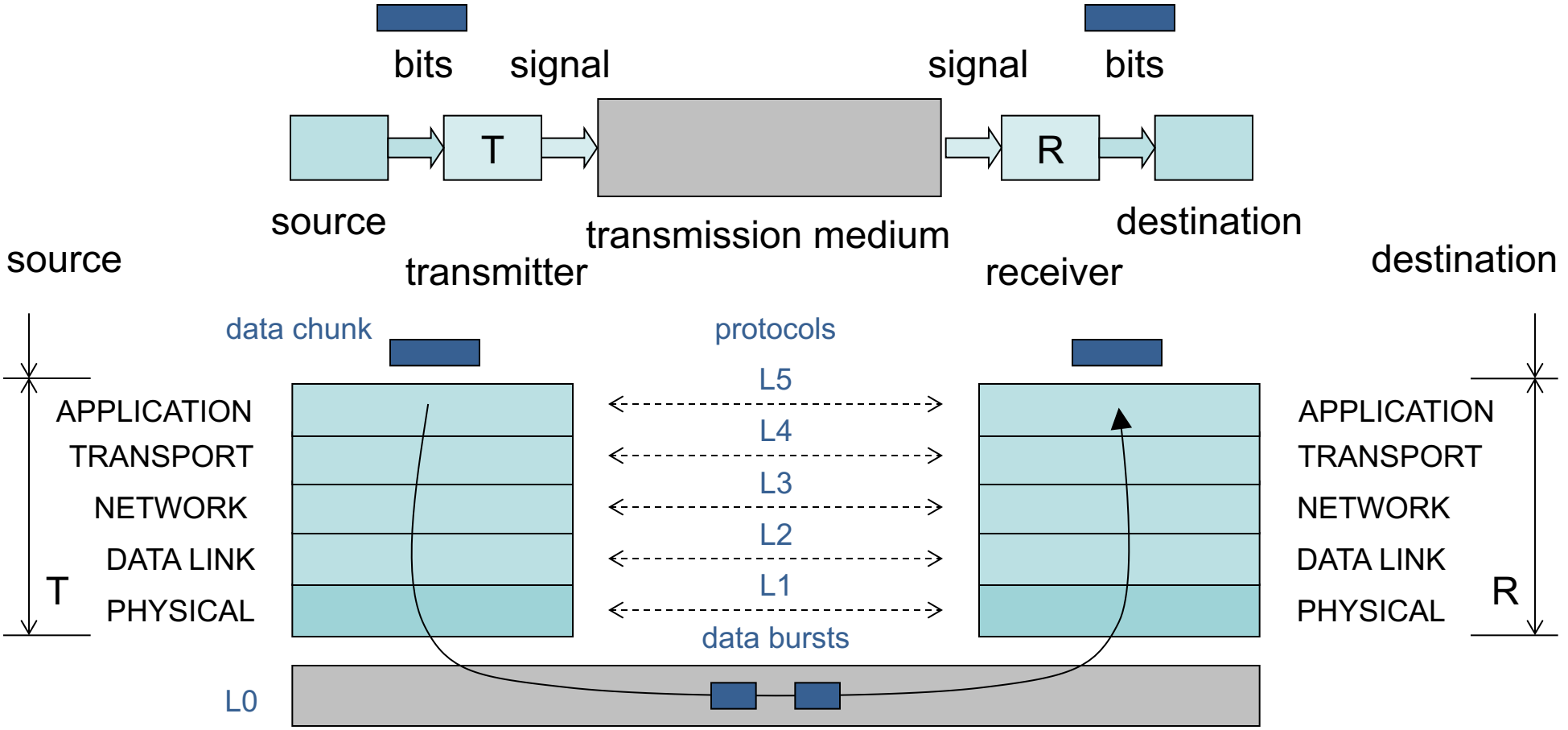
# Fundamentals of Digital Communications

## Digital Communications → Protocols



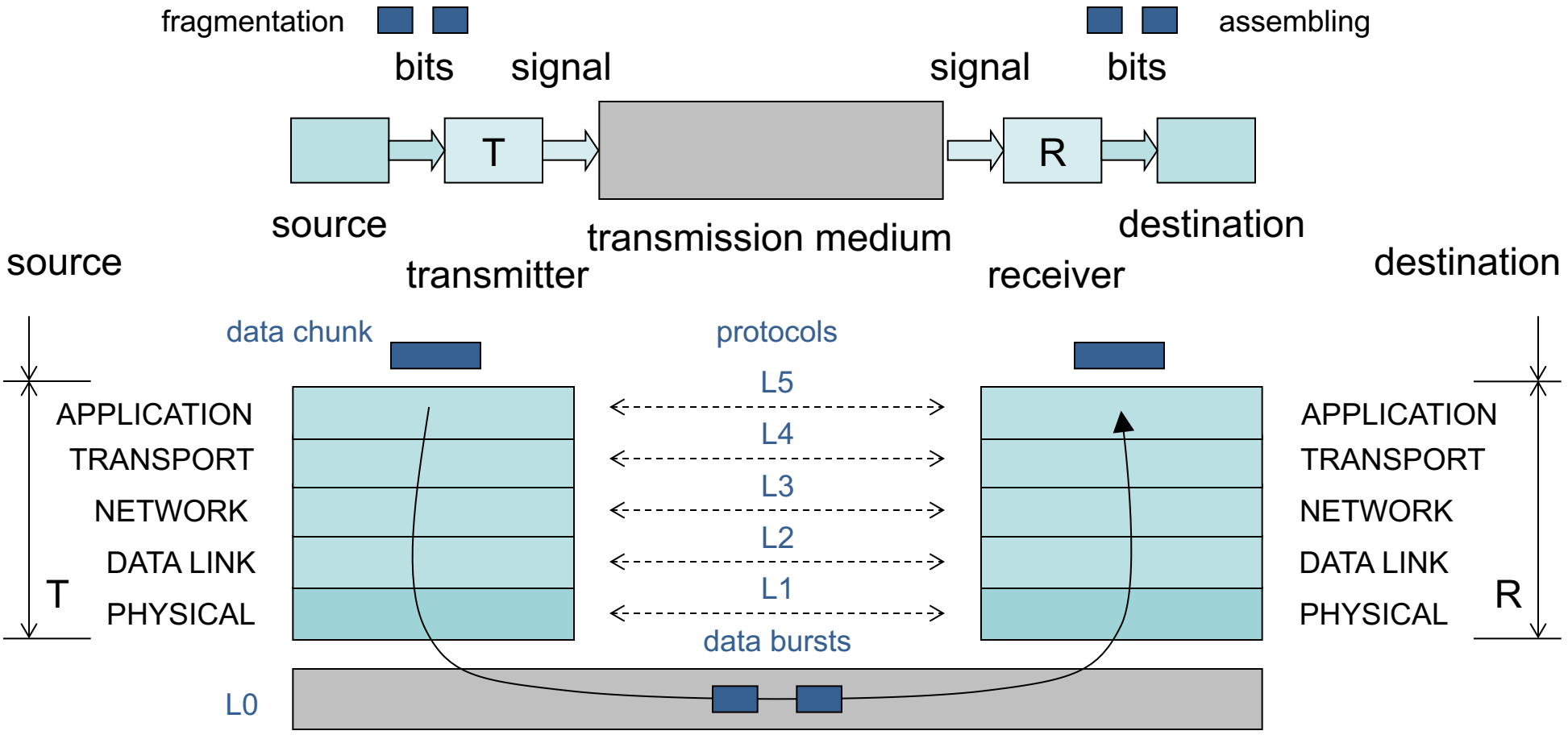
# Fundamentals of Digital Communications

## Digital Communications → Protocols



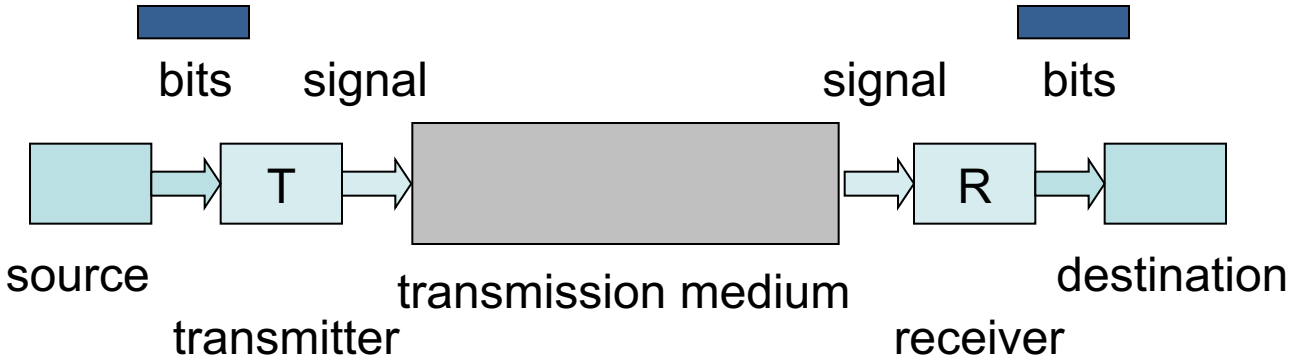
# Fundamentals of Digital Communications

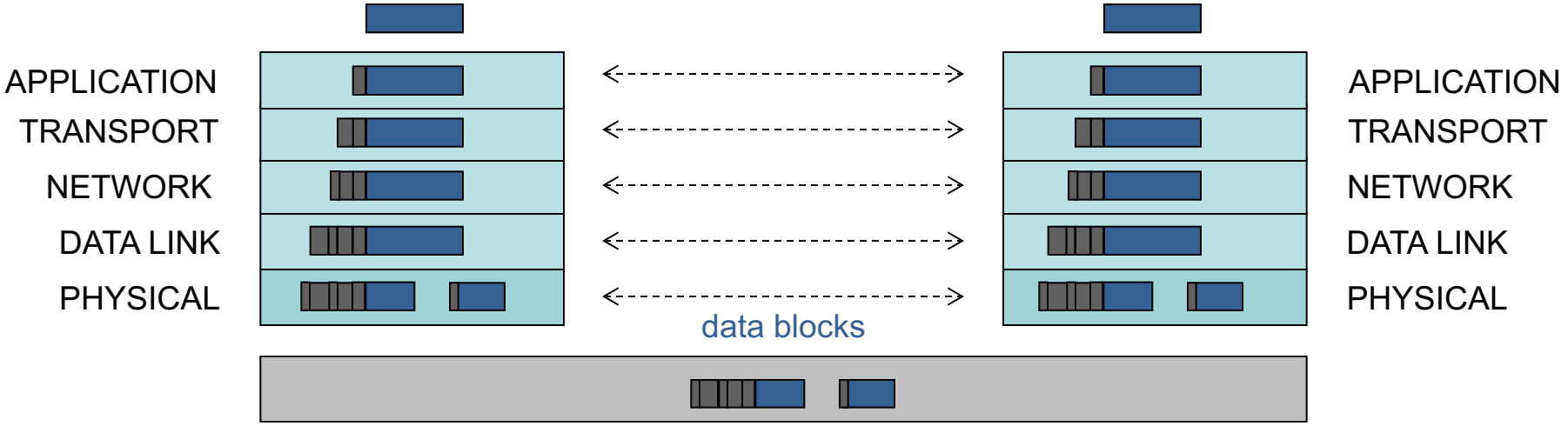
## Digital Communications → Protocols



# Fundamentals of Digital Communications

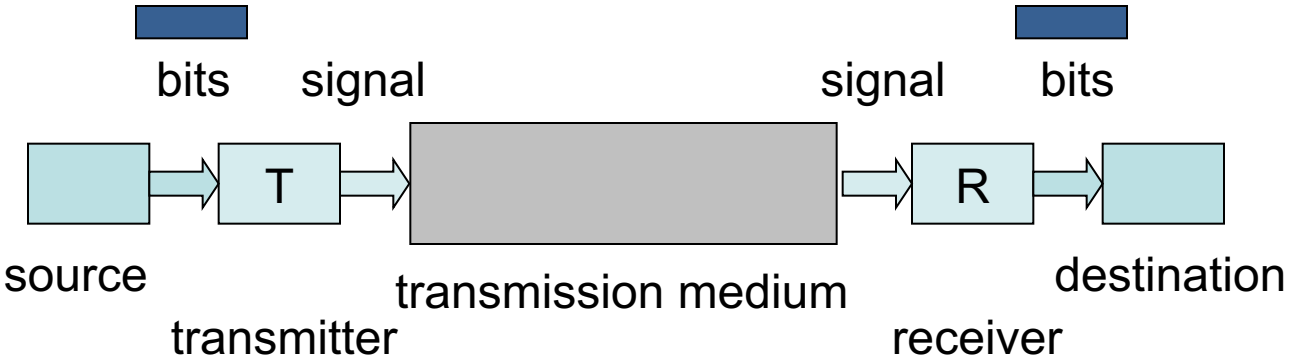
## Digital Communications → Protocols

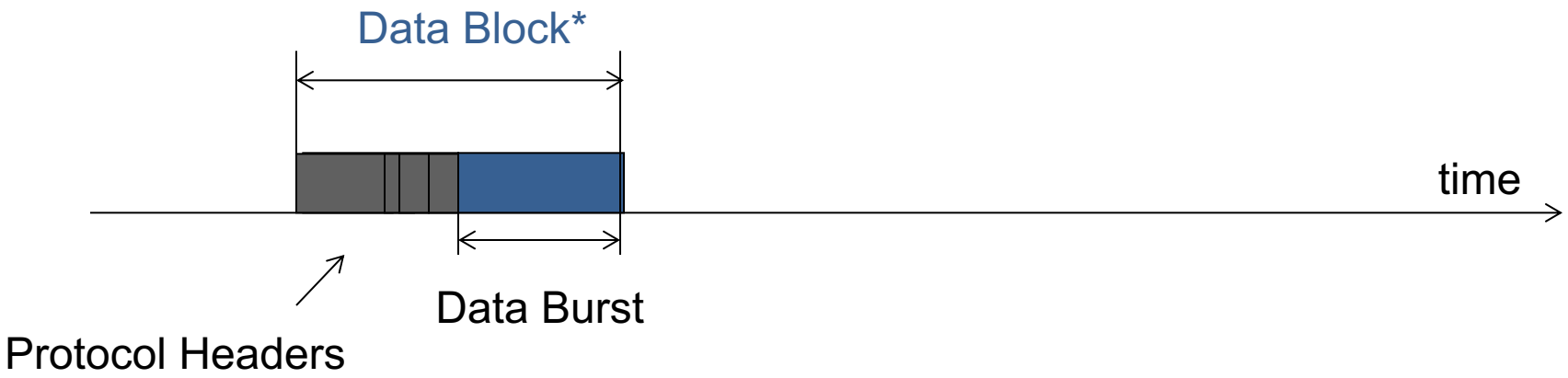


# Fundamentals of Digital Communications

## Digital Communications → Protocols

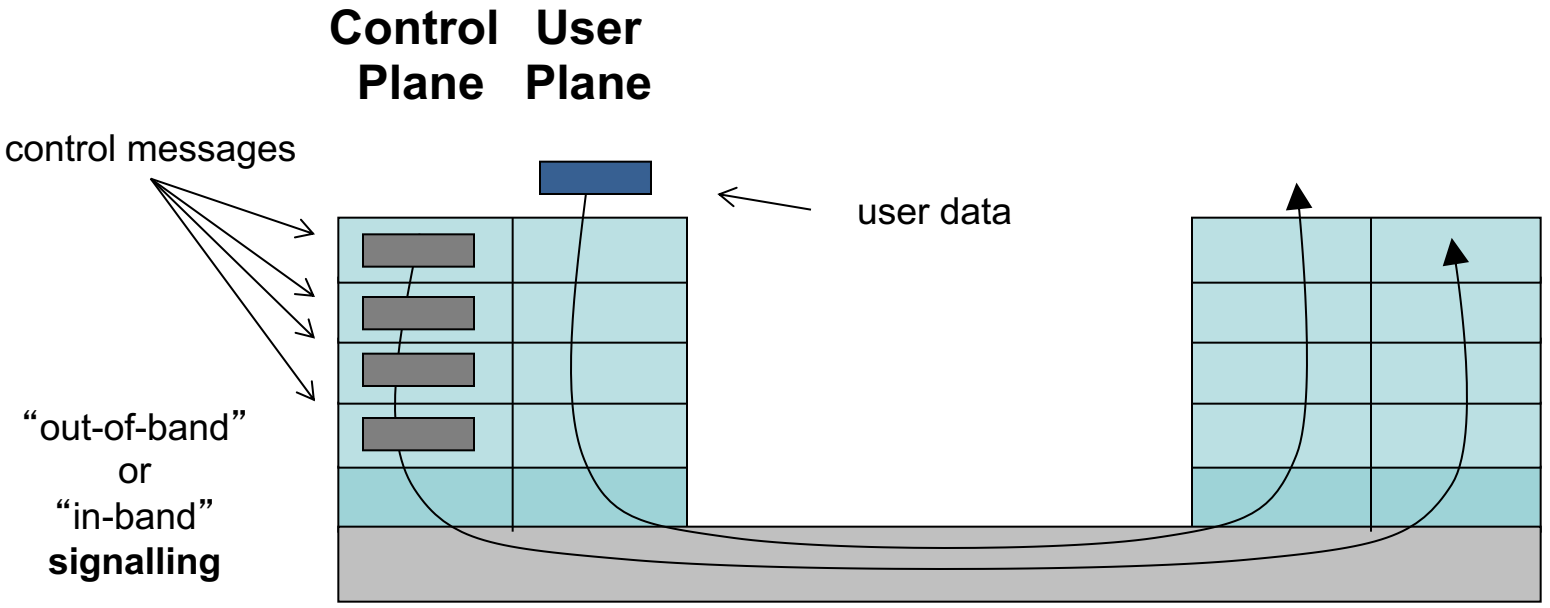



** Sometimes erroneously denoted as Packet. Packets are L3 entities.*

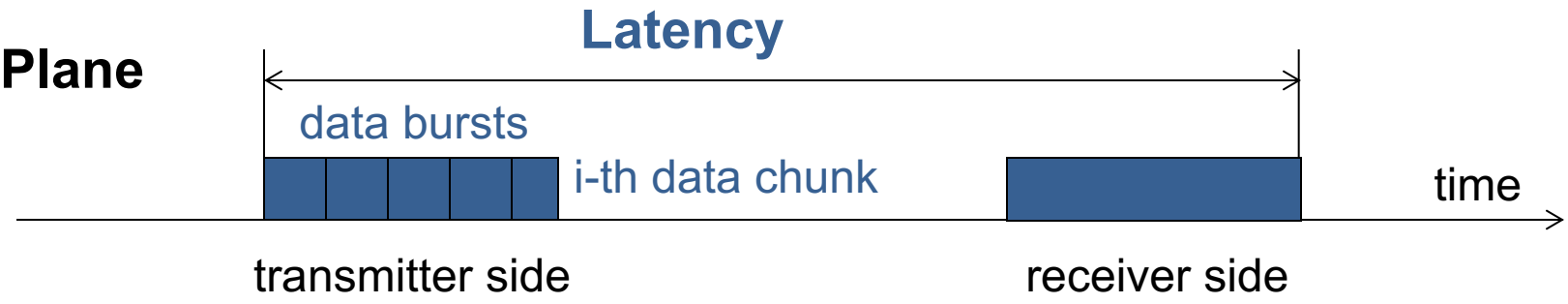
# Fundamentals of Digital Communications

## Digital Communications → Protocols

# Fundamentals of Digital Communications

**Digital Communications → Protocols**




**Rb = Bit Rate = number of bits per second transmitted on the channel.**

**U = User Throughput = number of information bits per second successfully received by the destination.**

**W = Latency = time to transfer a data chunk from source to destination.**

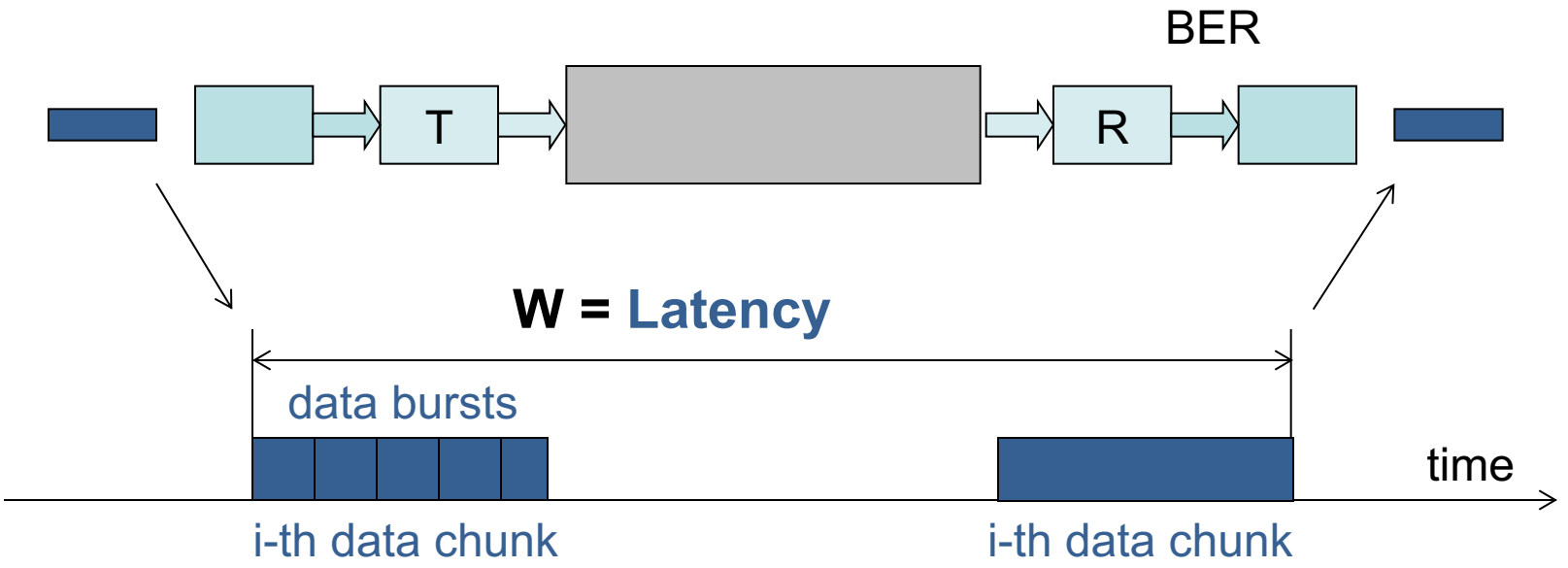
# Fundamentals of Digital Communications

**Digital Communications → Application Requirements**

# Fundamentals of Digital Communications

## Digital Communications → Application Requirements

### User Plane



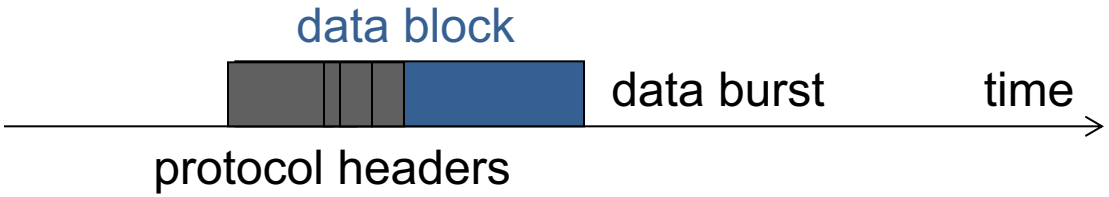

**U = User Throughput = Number of information bits per second received**

**BER = Bit Error Rate = Percentage of erroneous bits**

# Fundamentals of Digital Communications

## Digital Communications → Application Requirements

### User Plane

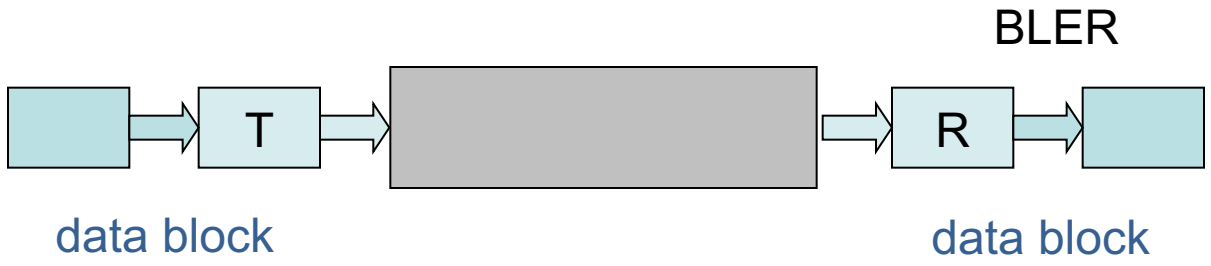

Three main options:

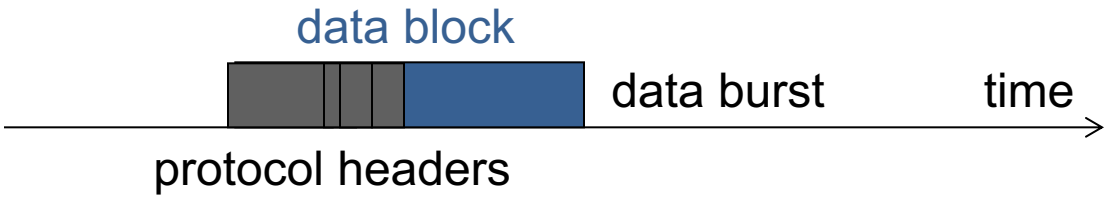
1. All bits are correct
2. Errors are correctable
3. To be discarded
4. Only partially discarded

# Fundamentals of Digital Communications

## Digital Communications → Application Requirements

### User Plane



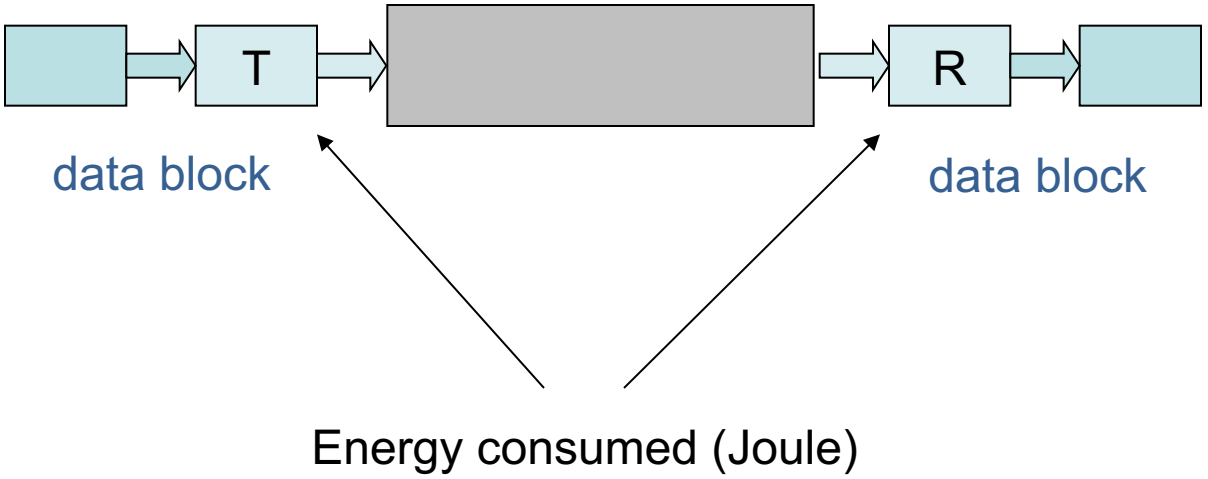




**BLER = BLock Error Rate = Percentage of erroneous data blocks**

# Fundamentals of Digital Communications

**Digital Communications → Application Requirements**

**Both Planes**




**EE = Energy Efficiency = Number of information bits per joule received**

# Fundamentals of Digital Communications

## Digital Communications → Application Requirements


**Some examples**

| | Interactive audio | Interactive video | web browsing | control |
|---|---|---|---|---|
| user throughput | 10 Kbit/s | 100 Kbit/s | n. a. | n. a. |
| latency | 300 ms | 500 ms | n. a. | 0.1-10 ms |
| BLER | 0.05 | 0.01 | zero | 0.0001 |

# Fundamentals of Digital Communications

**Digital Communications → Application Requirements**


**BLER**

**Energy Efficiency**


**Latency**

**User Throughput**

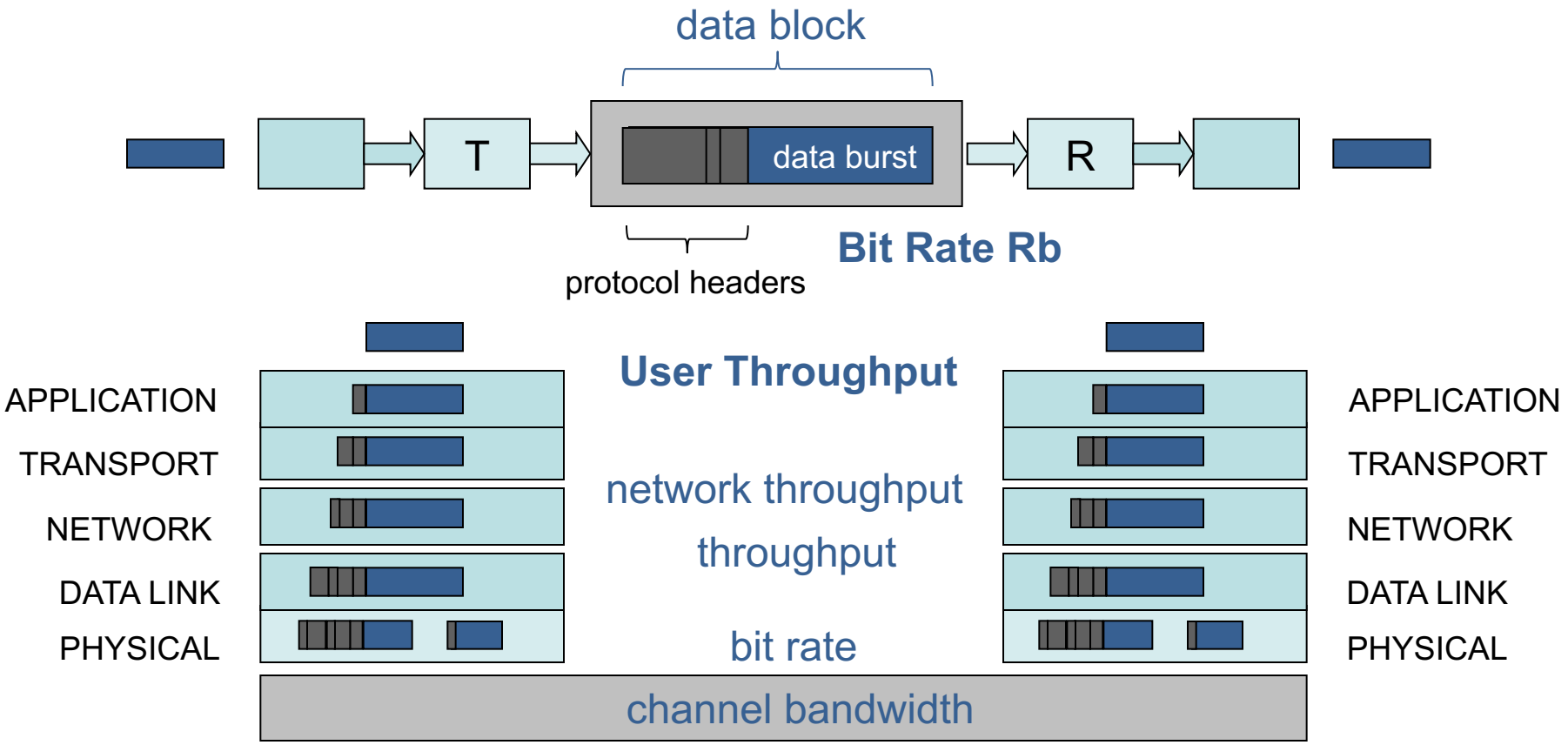
**… with different levels of reliability (BLER).**

# Fundamentals of Digital Communications

**Digital Communications → Protocol Efficiency**

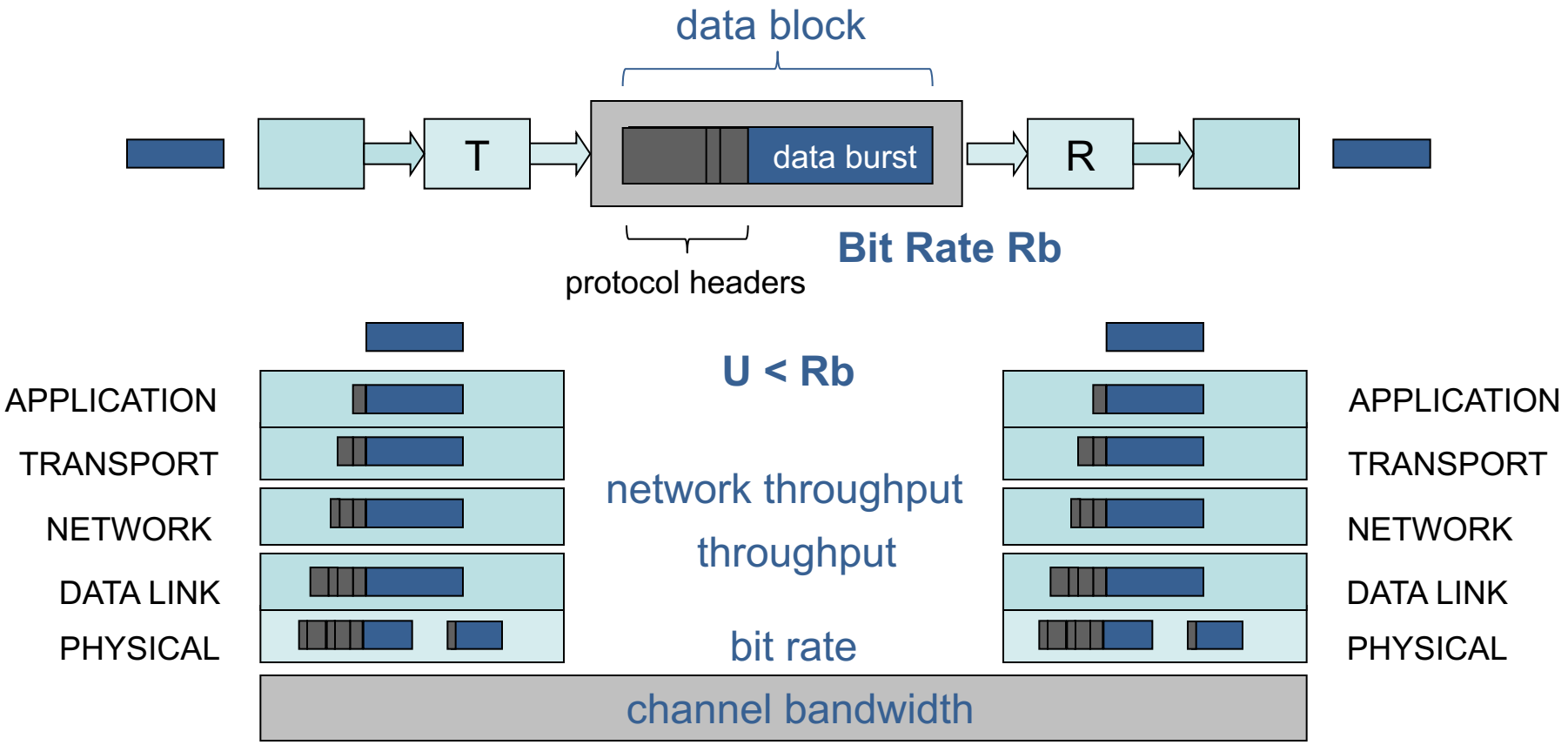
# Fundamentals of Digital Communications

## Digital Communications → Protocol Efficiency



# Fundamentals of Digital Communications

## Digital Communications → Protocol Efficiency

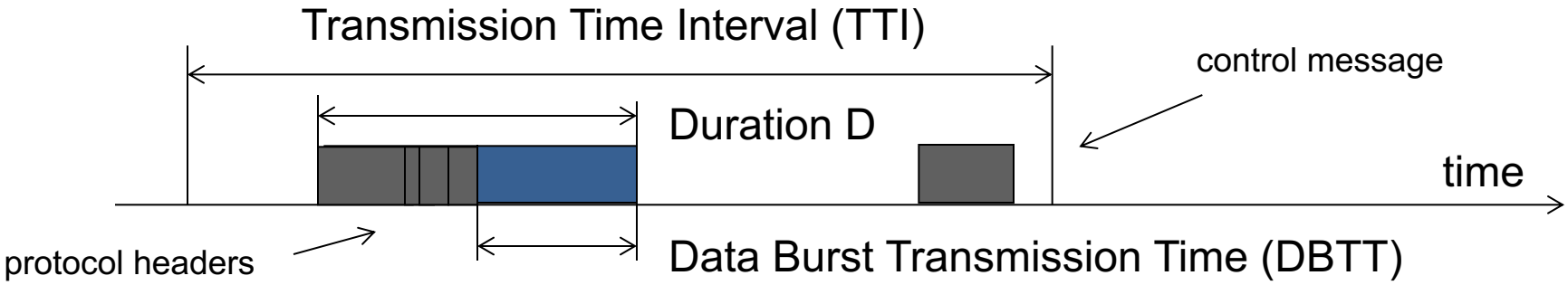


# Fundamentals of Digital Communications

**Digital Communications → Protocol Efficiency**

**U < Rb for three reasons:**

1. **protocol headers (redundancy)**
2. **control messages (overhead)**
3. **silent intervals (overhead)**




**Protocol Efficiency = $\eta_p$ = DBTT / TTI < 1**

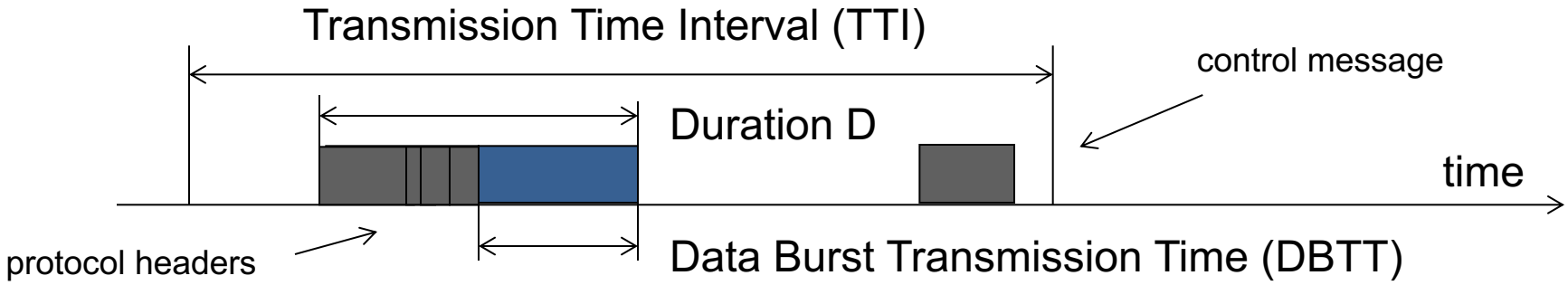
**User Throughput = Rb * $\eta_p$ < Rb** **(ideal channel conditions)**

# Fundamentals of Digital Communications

**Digital Communications → Protocol Efficiency**

**U < Rb for three reasons:**

1. **protocol headers (redundancy)**
2. **control messages (overhead)**
3. **silent intervals (overhead)**



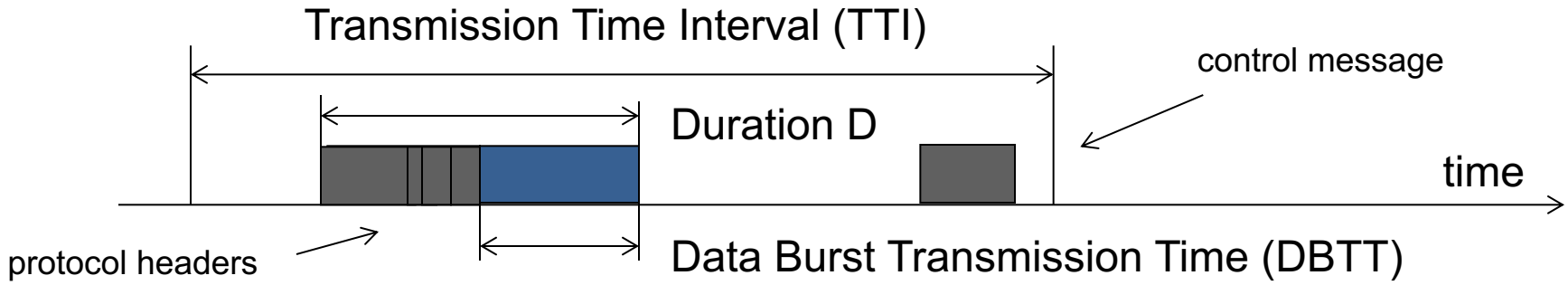

**Redundancy Factor = $\eta_r$ = DBTT / D < 1**
**Overhead Factor = $\eta_o$ = D / TTI < 1**

# Fundamentals of Digital Communications

**Digital Communications → Protocol Efficiency**

**U < Rb for three reasons:**

1. **protocol headers (redundancy)**
2. **control messages (overhead)**
3. **silent intervals (overhead)**

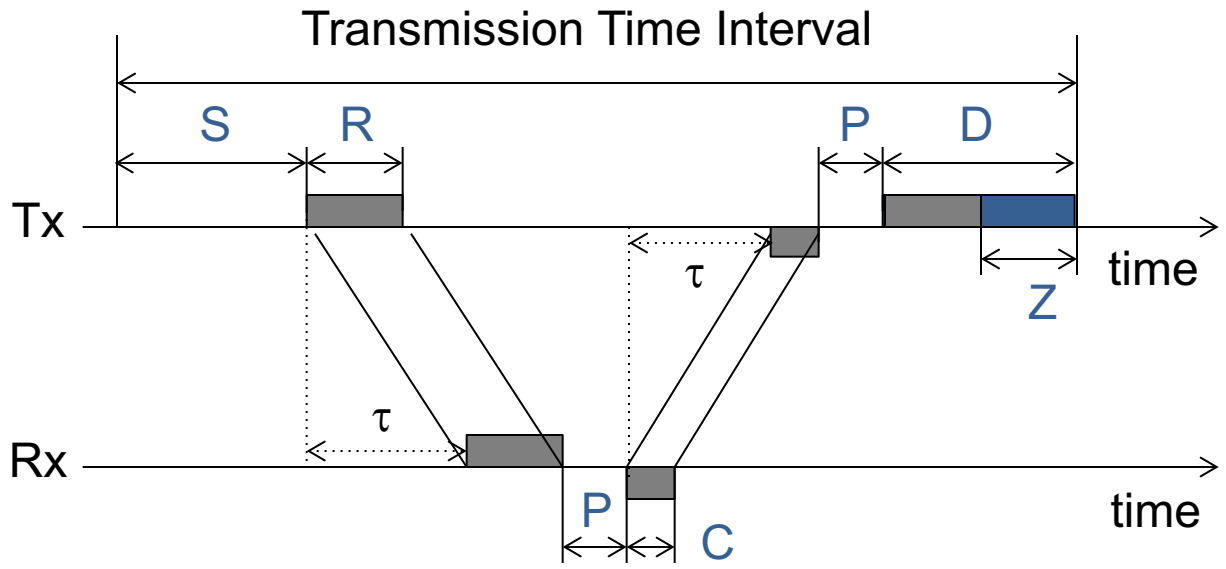



**Protocol Efficiency = $\eta_p$ = DBTT / TTI = $\eta_r$ $\eta_o$**

# Fundamentals of Digital Communications

**Digital Communications → Protocol Efficiency**

**e.g. CSMA with RTS/CTS**

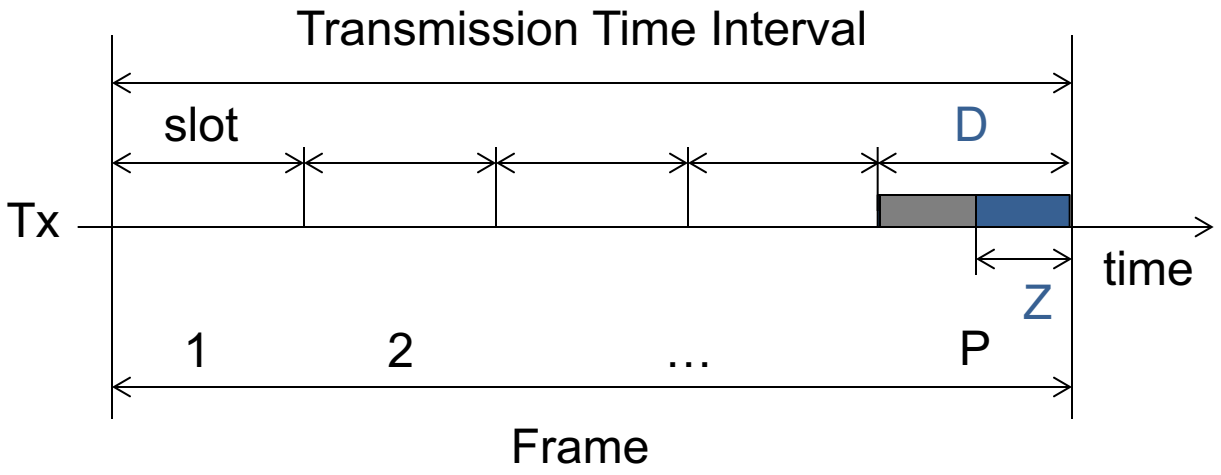



**Protocol Efficiency = $\eta_p$ = Z / [ Z + (S+R+C+(D-Z)+2P+2$\tau$) ]**
**E.g. in WiFi $\eta_p \cong$ 1 / [ 1 + (S+2$\tau$)/Z] ≅ 0.5 with large data bursts (1 KB)**

# Fundamentals of Digital Communications

**Digital Communications → Protocol Efficiency**

**e.g. TDMA**

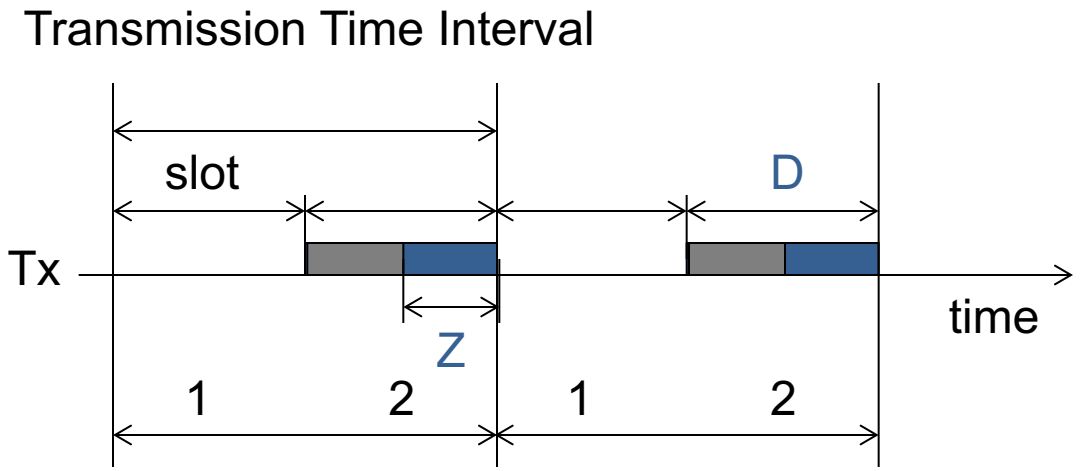



**Protocol Efficiency = $\eta_p$ = Z / P D = $\eta_a$ * Z / D = $\eta_a$ * $\eta_r$**
**E.g. in 2G $\eta_p \cong 0.04$ when using only one slot over eight**

# Fundamentals of Digital Communications

**Digital Communications → Protocol Efficiency**

**e.g. TDD**




**Protocol Efficiency = $\eta_p$ = Z / 2 D = $\eta_d$ * Z / D = $\eta_d$ * $\eta_r$**
**E.g. in Bluetooth $\eta_p \cong 0.25$ when only one slave is connected to a master**

# Fundamentals of Digital Communications

**Digital Communications → Protocol Efficiency**


$$\eta_p = \eta_r * \eta_o$$

$\eta_r$ **Redundancy Factor**
$\eta_o$ **Overhead Factor**

# Fundamentals of Digital Communications

## Digital Communications → Protocol Efficiency


$$U = Rb * \eta_p * ( 1 - BLER )$$

**Higher user throughputs require:**

- Larger bit rates
- More efficient protocols
- Reliable channels