Multiplexing

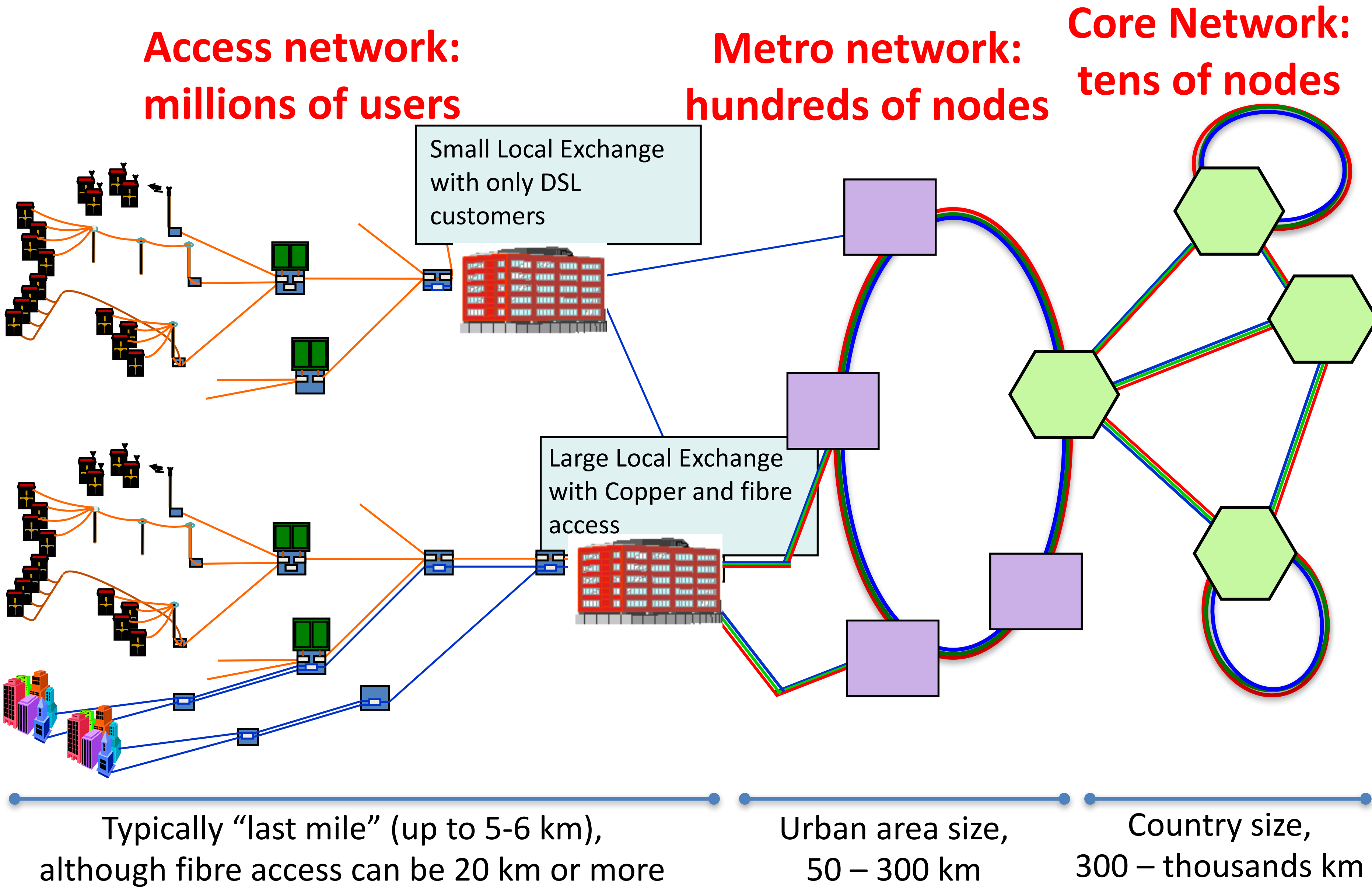
Signal multiplexing

- Multiplexing is the set of techniques that allows the simultaneous transmission of multiple signals across a single data link.

- We have seen that a telecommunications network is made up of:
  - an access part, where each user might have an individual data link
  - a metro part that aggregates user traffic
  - A core part that further aggregates and transport traffic to far away destinations

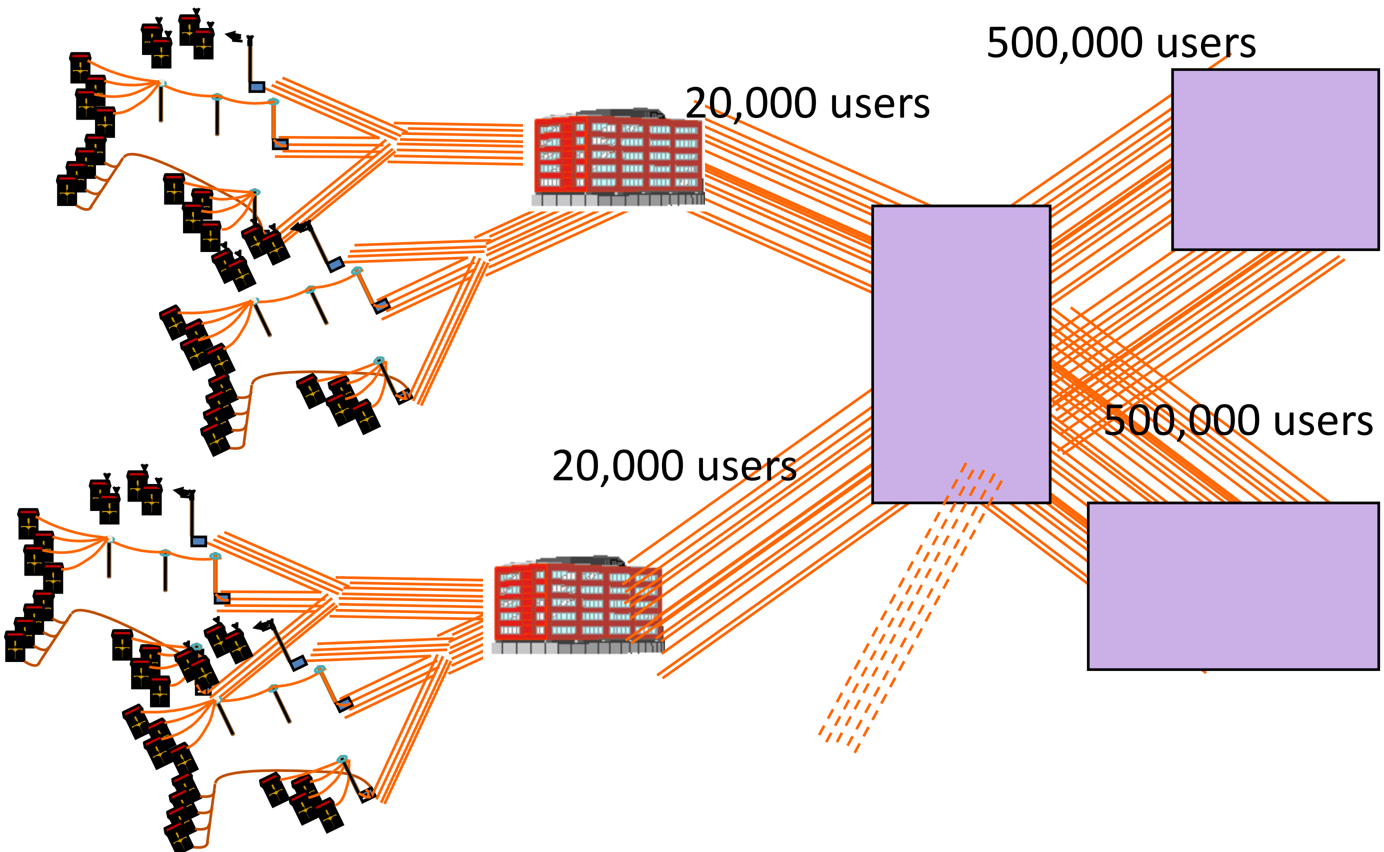
- Multiplexing allows the aggregation of access->to metro-> to core at the physical layer

Traffic is progressively aggregated from Access to Metro to Core



Hypothetic example

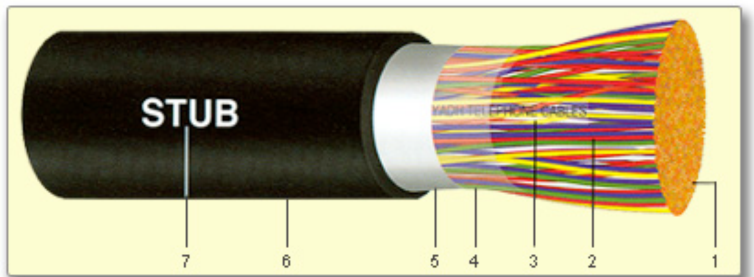
- Each phone connects with a twisted pair to the central office. **If** each conversation stays on a different wire, at the metro nodes we **would have** hundred of thousand of wires…



This is not feasible, so this solution cannot be used and a better solution is required

Hypothetic example

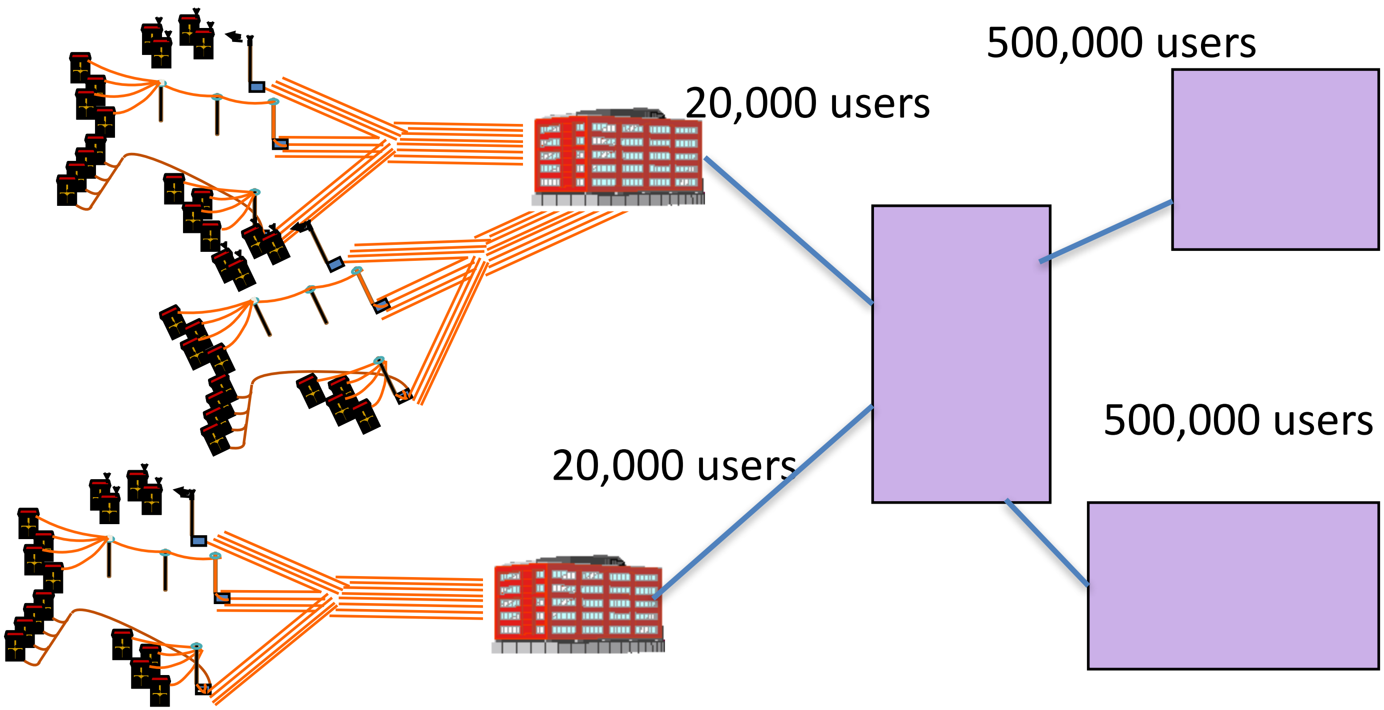
- Even if we used highly compressed copper cables



- 400 wires can fit in a cable that is 4.5cm in diameter, and weight 3 tons per Km
- For 500,000 we would require 1250 such cables, with a size of about 2 meters in diameter and a weight of 3750 tons per km
- And 500,000 is a relatively small number… think of countries like the US…

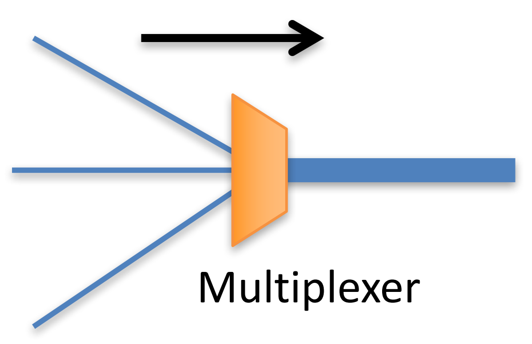
Traffic aggregation with signal multiplexing

- The signals incoming from the users can all be multiplexed into one or a few cables



Medium capacity

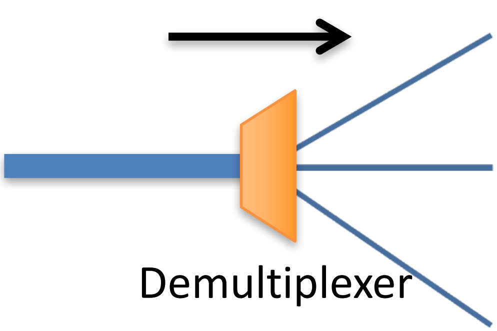
- Notice that the medium where other signals are multiplexed needs to have **enough capacity** to support all incoming signals
- This means that the bandwidth or capacity of the downstream medium needs to be at least equal to the sum of the bandwidth or capacity of the incoming signals.
- The concept is similar to water pipes: the pipe where all other flows converge needs to have enough capacity to support them



Demultiplexing

- Demultiplexing is the inverse operation

- I have a cable carrying many multiplexed signals and I want to separate them into its individual components…
  - But unlike water, I need to send each information flow in the right direction



Types of multiplexing

- We are going to introduce two types of multiplexing:
- Frequency division multiplexing (FDM):
  - When operated in the optical domain is called wavelength division multiplexing (WDM)
- Time division multiplexing (TDM)
- **The important thing is that the multiplexed signals don’t overlap in frequency (for FDM) or in time (for TDM), otherwise I can’t separate them at the end of the link**

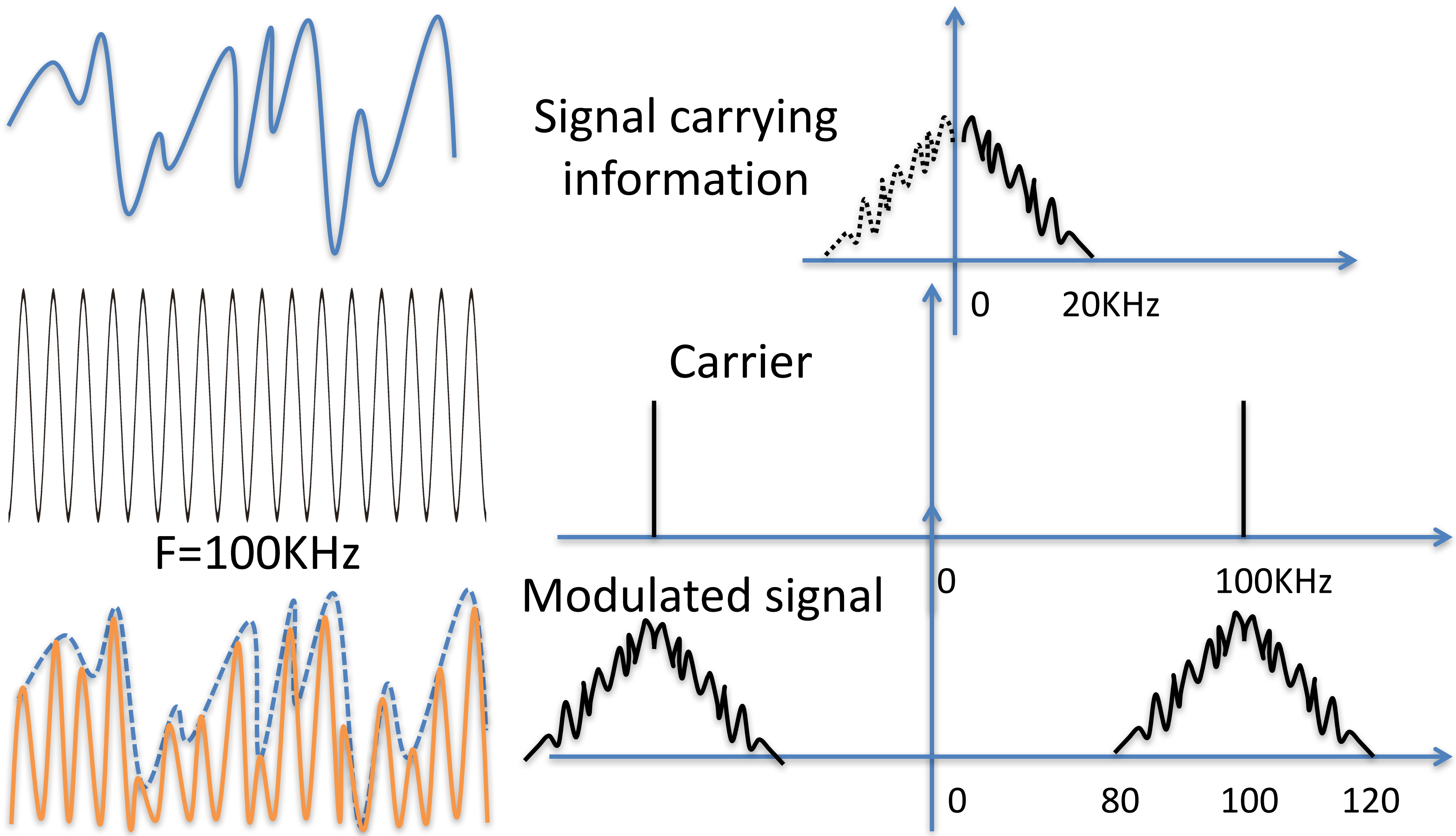
FDM

- FDM is carried out by modulating the signal with one of the modulations schemes we have encountered:
  - Analog modulations (AM, FM, PM)
  - Digital Modulations (ASK, FSK, PSK, QAM)

- Recall that modulating a signal moves its spectrum towards higher frequencies

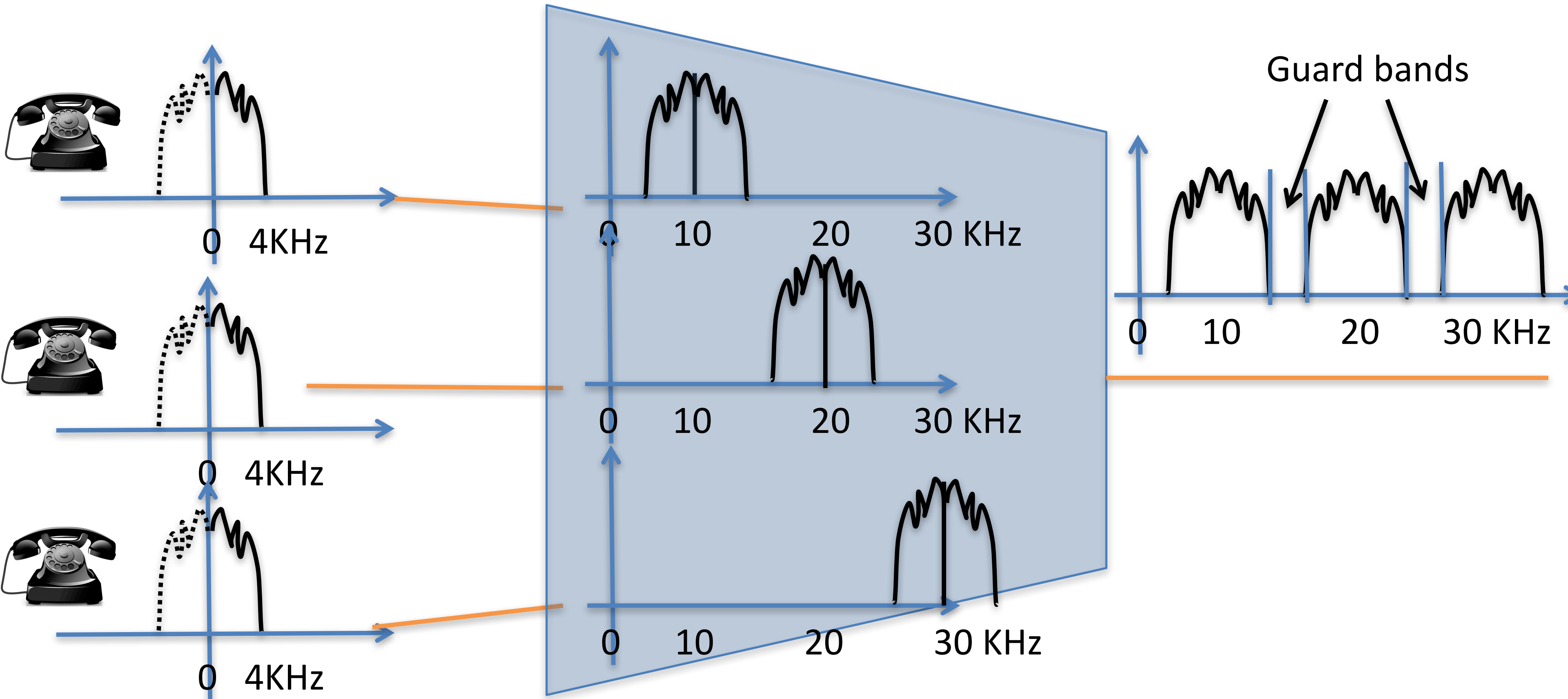
Spectrum of a modulated signal

Time domain **Spectrum domain**



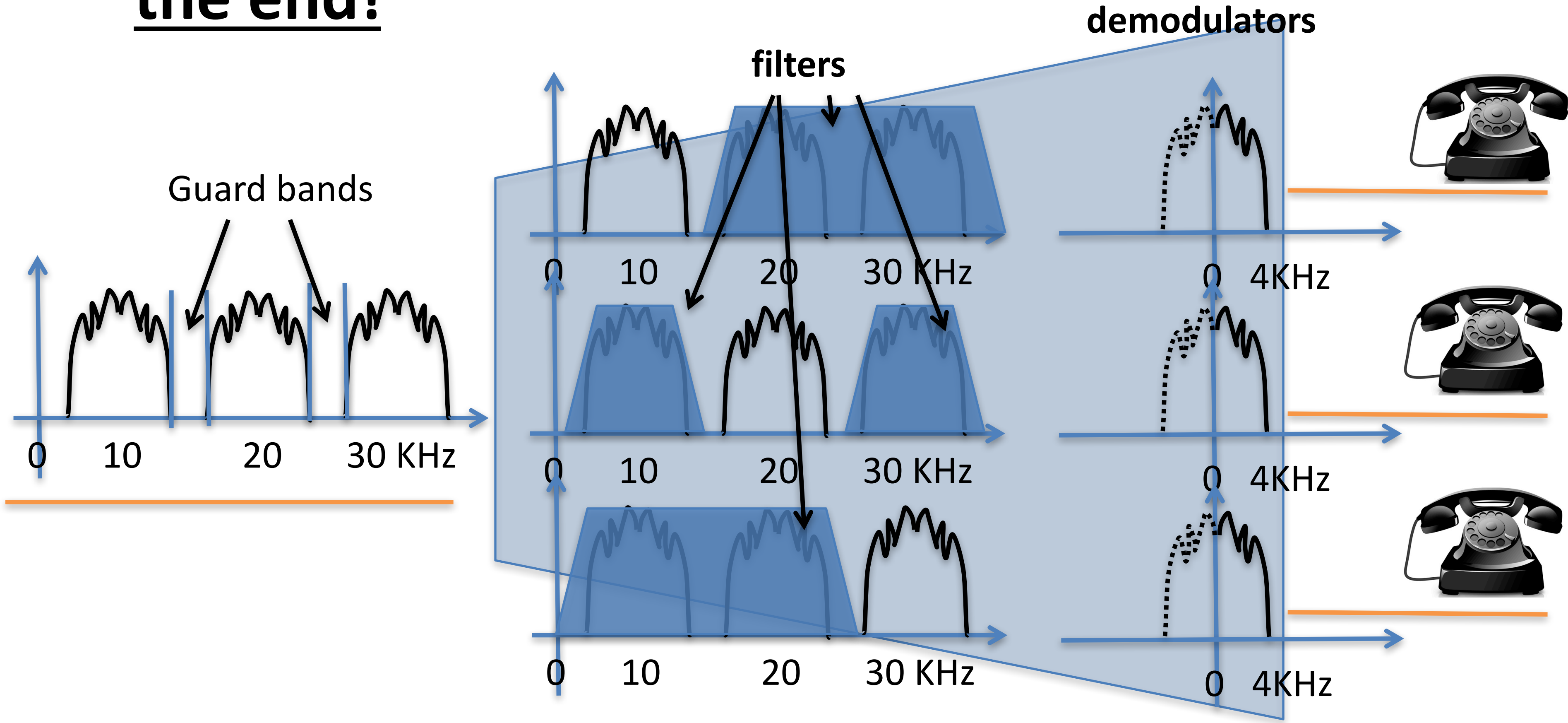
FDM - Multiplexing

- If we use a different carries for each signal, whose spacing is higher than the signal bandwidth, the spectra of the signals don't overlap



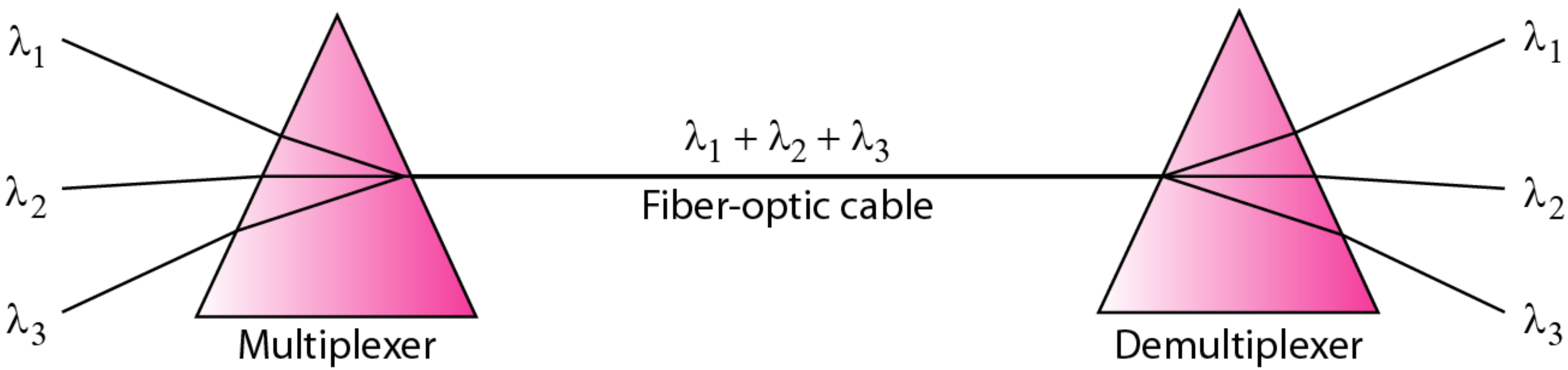
FDM - Demultiplexing

- **<u>Important: as far as the frequencies don't overlap, I can separate (filter) the signals at the end!</u>**



Wavelength Division Multiplexing (WDM)

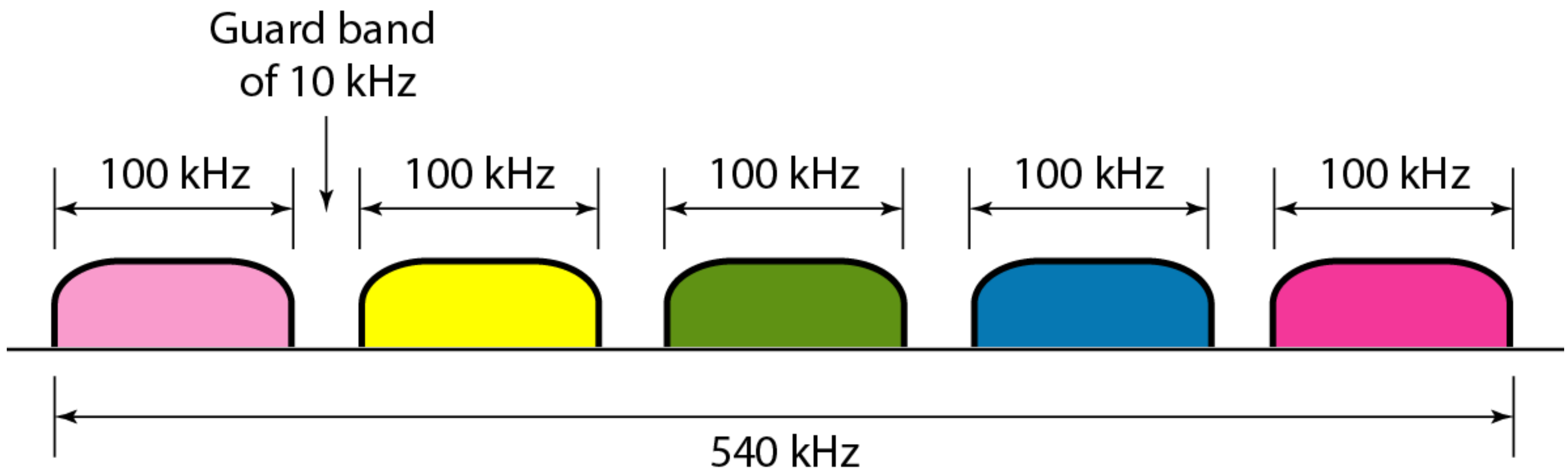
- Wavelength division multiplexing is the same as FDM but applied to optical fibre transmission.
- The carrier used to modulate the signals are expressed in terms of their wavelengths λ instead of their frequency f.



Example

- Five channels, each with a 100-kHz bandwidth, are to be multiplexed together. What is the minimum bandwidth of the link if there is a need for a guard band of 10 kHz between the channels to prevent interference?

Solution

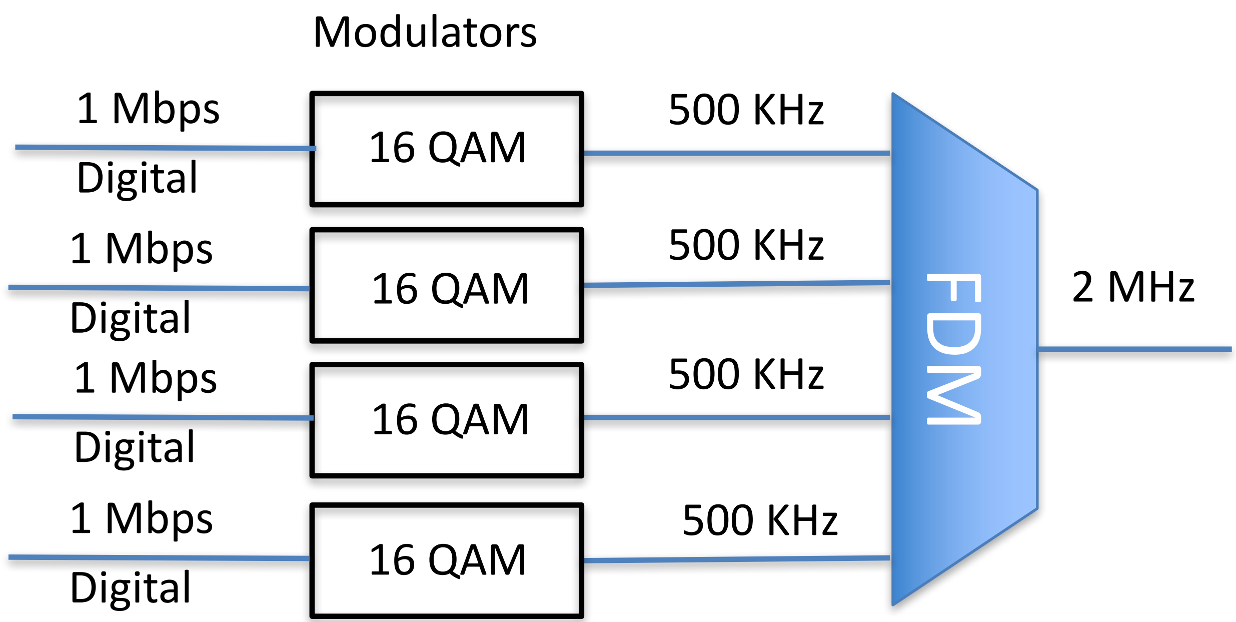


For five channels, we need at least four guard bands. This means that the required bandwidth is at least $5 \times 100 + 4 \times 10 = 540$ kHz.

Example

- Four data channels (digital), each transmitting at 1 Mbps, need to be multiplexed into a satellite channel with a capacity of 2 MHz.
- Design an appropriate configuration, using FDM, considering d=1 for the modulation.

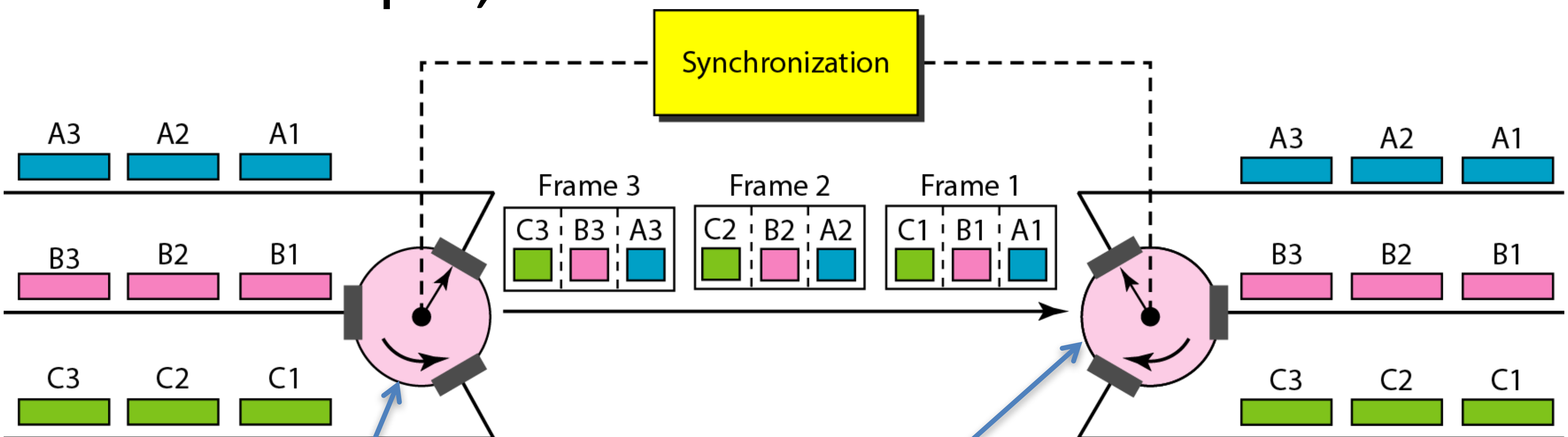
Solution



- B_{mod}=(1+d) x S, R=S x $\log_2 L$ ➔ B_{mod}=(1+d) x R / $\log_2 L$
  ➔ $\log_2 L$=(1+d) x R /B_{mod}
- If we consider d=1 ➔ $\log_2 L$ =2 x 1Mbps/ 500 KHz =4 ➔ L=2^4=16
- We divide the satellite channel into four channels, each channel having a 500-kHz bandwidth. Each digital channel of 1 Mbps is modulated so that each 4 bits is modulated to 1 Hz. One solution is 16-QAM modulation.

Time Division Multiplexing (TDM)

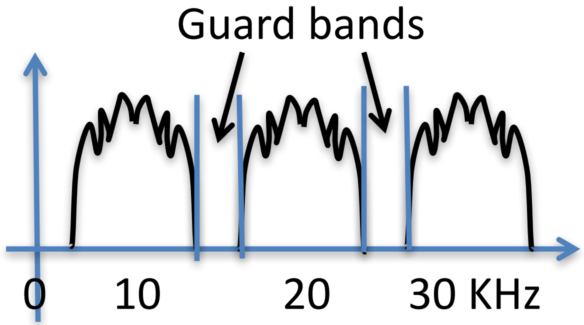
- In TDM, the medium is divided into time slots, and each user gets assigned one slot every n.
- For example, if we have three users:



- Multiplexer and demultiplexer need to be synchronized, in order to send the right bits to the right user.

TDM Bandwidth

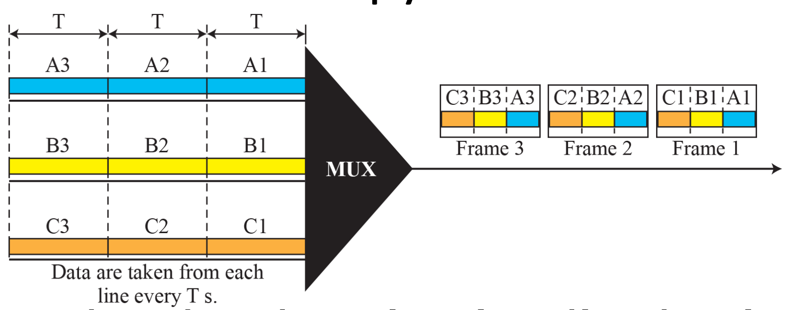
- We said that multiplexing requires a channel with bandwidth at least equal to the sum of the bandwidths of the incoming signals (plus a guard band).
- In FDM this is quite clear:

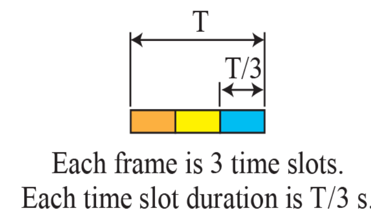


- But why do we need more bandwidth in TDM??

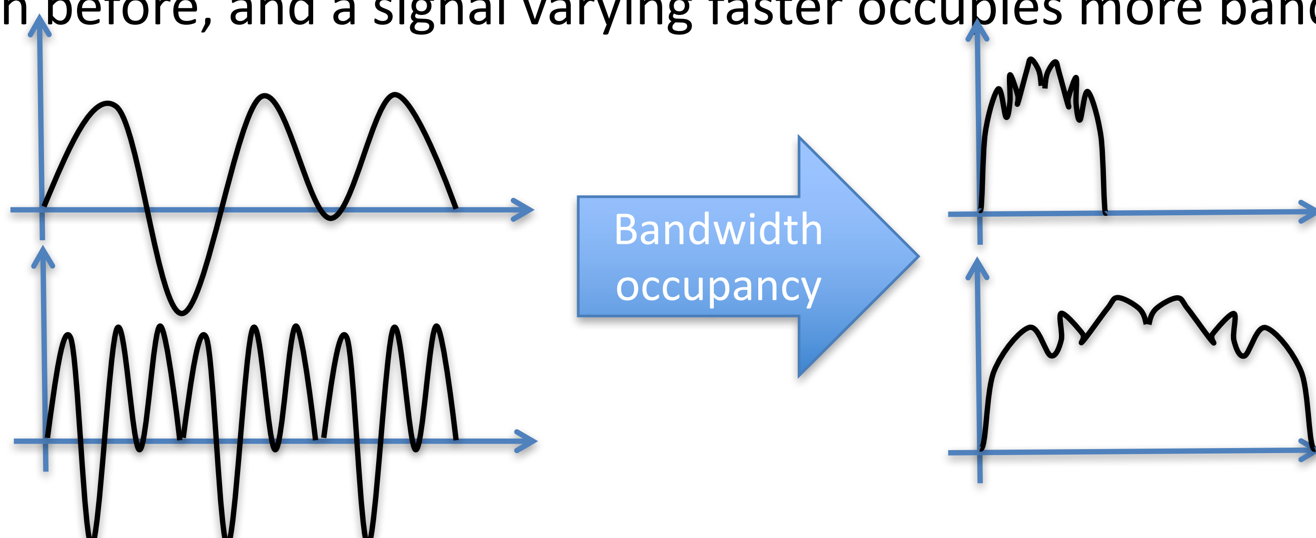
TDM Bandwidth

- Each incoming signal will have a certain rate, say 1 Mb/s.
  - This means that each bit can occupy a maximum of 1s/1,000,000 = 1us.
- If however we want to send three channels in the same time, we need each slot to occupy a maximum of 1us/3 = 0.33 us.



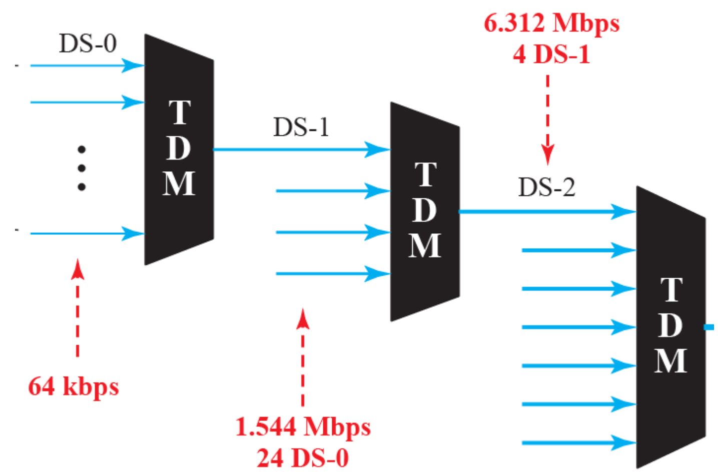


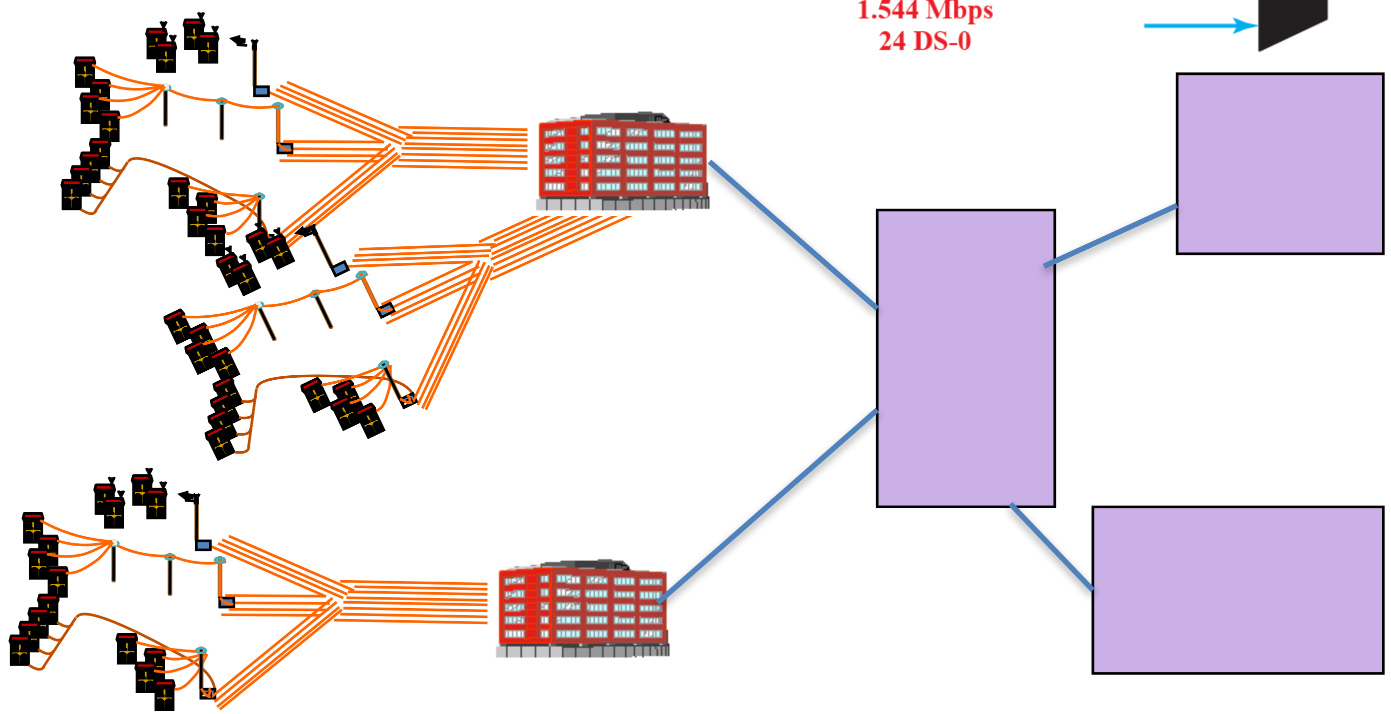
- Reducing the slot duration implies having a signal that varies faster than before, and a signal varying faster occupies more bandwidth.



Multi-level multiplexing

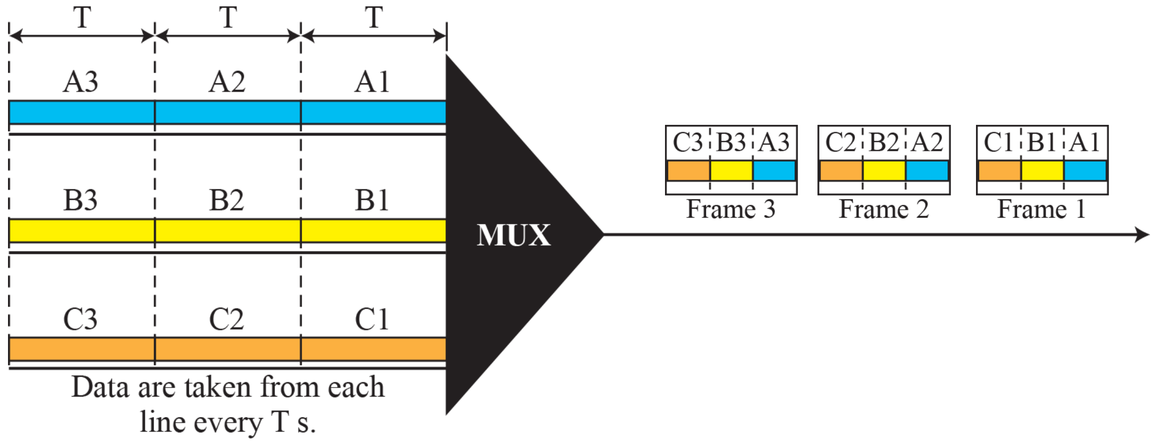
- Each stage can be at a different location, progressively aggregating more and more channels





Example

- In the figure, the data rate for each input connection is 1 kbps. If 1 bit at a time is multiplexed (a unit is 1 bit), what is the duration of
  - 1. each input slot,
  - 2. each output slot, and
  - 3. each frame?



Solution

1. The data rate of each input connection is 1 kbps. This means that the bit duration is 1/1000 s or 1 ms. The duration of the input time slot is 1 ms (same as bit duration).

2. The duration of each output time slot is one-third of the input time slot. This means that the duration of the output time slot is 1/3 ms = 0.333 ms.

3. Each frame carries three output time slots. So the duration of a frame is 3 × (1/3) ms, or 1 ms. The duration of a **frame** is the same as the duration of an input unit.

Static multiplexing vs statistical multiplexing

- Notice that this type of multiplexing is static (both TDM and FDM), meaning that the channel is assigned to the user even if it’s not used, until the channel is released
  - E.g., this was typical of TDM voice transmission systems

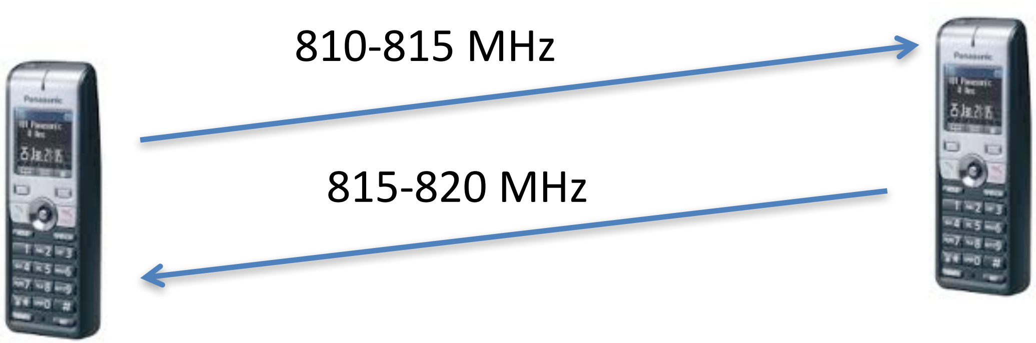
- Data networks are different and use a concept called statistical multiplexing:
  - The downstream link has more capacity than each incoming link but (quite a bit) less than the sum of them
  - The idea is that not all incoming links will be running at full capacity all time..
  - The Internet is based on this idea… although you will see more of this over the next years

Duplexing

- Duplexing indicates the way a communication between two points is handled on the two opposite directions:
  - Half-duplex: only one direction of communication is allowed at any one time (e.g., push-to-talk radio)
  - Full-duplex: the communication can be active on the two directions simultaneously (e.g., telephone)

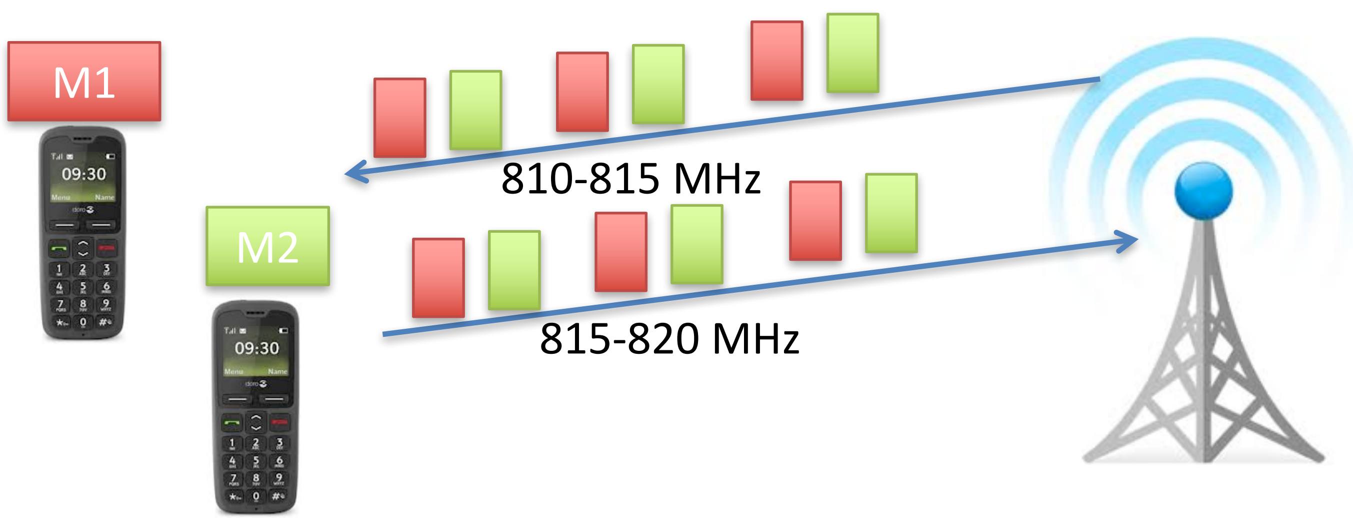
Full-duplex implementation

- Full-duplex can be implemented using either a frequency-division approach or a time-division approach.
- In frequency-division duplex, the two directions of communications are implemented using different frequency channels



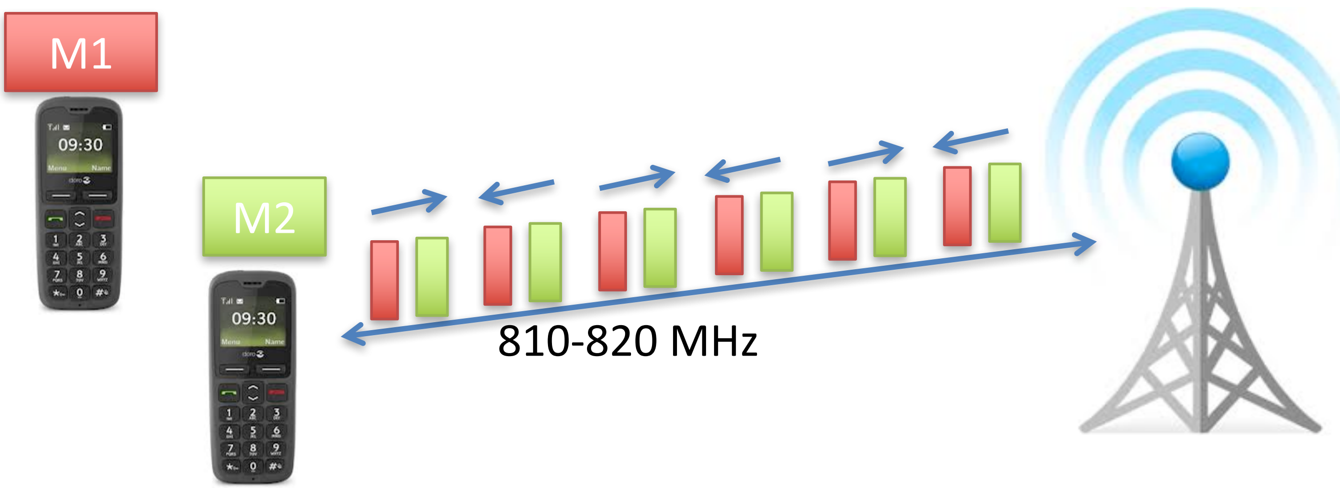
Frequency-division duplex (FDD)

- FDD is also used in some cellular systems, where two separate frequency bands are used for the two direction and each frequency band uses TDM to allocate multiple users



Time-division duplex (TDD)

- Time-division duplex is achieved by separating the two direction using time division multiplexing.
- Only one frequency band is used, and the time slots are split between upstream and downstream directions.



- Notice that in order to fit both directions in the same time as with the FDD, the slots are smaller, which explain the increase in occupied bandwidth in the example from 5 MHz to 10 MHz

Comparison

Frequency-division duplex	Time-division duplex
Frequency bands are statically allocated, so it does not accommodate asymmetric links very well	Making links asymmetric is very easy, as I can decide to split the number of slots available to upstream and downstream arbitrarily
If the bandwidth required is always symmetric FDD is more efficient	some time is wasted in guard intervals when swapping directions
The circuitry is simpler as upstream and downstream directions do not need synchronization	Tight time synchronization is required among the two communication directions

Often TDD is preferred where data transmission is involved (practically all cellular systems today), as it allows dynamic reallocation of bandwidth allocated to upstream and downstream directions

Example

A communications system between two points uses FDD. The upstream direction requires 4Mb/s data rate, while the downstream requires 1Mb/s.

If the modulation used is a 4 QAM, and between the two frequencies there is a bandwidth gap of 500KHz, what is the total required bandwidth for the duplex communication?

- $B_{mod}=(1+d) \times S$, $R=S \times \log_2 L \Rightarrow B_{mod}=(1+d) \times R / \log_2 L$
- For upstream: if we consider d=1 $\Rightarrow B_{mod}=2 \times 4\text{Mbps}/\log_2 L =8/2 = 4$ MHz
- For downstream: if we consider d=1 $\Rightarrow B_{mod}=2 \times 1\text{Mbps}/\log_2 L =2/2 = 1$ MHz
- Summing up all bandwidths, including the guuard bandwidth, we require 1 + 4 + 0.5 MHz=5.5MHz