OMNeT++ Community Summit, 2019

An Efficient and Versatile Signal Representation in the INET Physical Layer

Hamburg University of Technology – Germany – September 04-06, 2019

Levente Mészáros

Motivation

- **INET 4** already provides several signal representations
  - Unit disk, scalar and dimensional
  - Dimensional model is based on **MiXiM**
- Problems with current dimensional model
  - **10+ times slower** than equivalent scalar model
  - Has open bugs which are very difficult to fix
  - Eager computation model makes it harder to speed up
  - Iterator API makes it difficult to extend

Benefits

- Representation for any kind of signals (time + frequency domains)
  - OFDM, FHSS, UWB, etc.
- Mix different wireless technologies arbitrarily
- Comparable performance to equivalent scalar representation and scale well for others
- Scale to large networks with small memory footprint
- Live visualization of transmission medium spectrum (space + time + frequency domains)

Live Demos

IEEE 802.11 – WIFI

IEEE 802.15.4 – WPAN

Hypothetical UWB

Network and Configuration

- No changes to the network

```
network CrosstalkShowcaseBaseNetwork
{
    submodules:
        physicalEnvironment: PhysicalEnvironment;
        configurator: Ipv4NetworkConfigurator;
        radioMedium: Ieee80211DimensionalRadioMedium;
        visualizer: IntegratedVisualizer;
        probe: Probe;
        sender1: AdhocHost;
        receiver1: AdhocHost;
        sender2: AdhocHost;
        receiver2: AdhocHost;
}
```

- Easily switch from scalar to multidimensional model

```
*.radioMedium.analogModel.typename = "DimensionalAnalogModel"
*.radioMedium.backgroundNoise.typename = "IsotropicDimensionalBackgroundNoise"
**.wlan[*].radio.typename = "Ieee80211DimensionalRadio"
```

```
**.analogModel.attenuateWithCarrierFrequency = false
**.errorModel.snirMode = "mean"
**.receiver.snirThresholdMode = "mean"
```

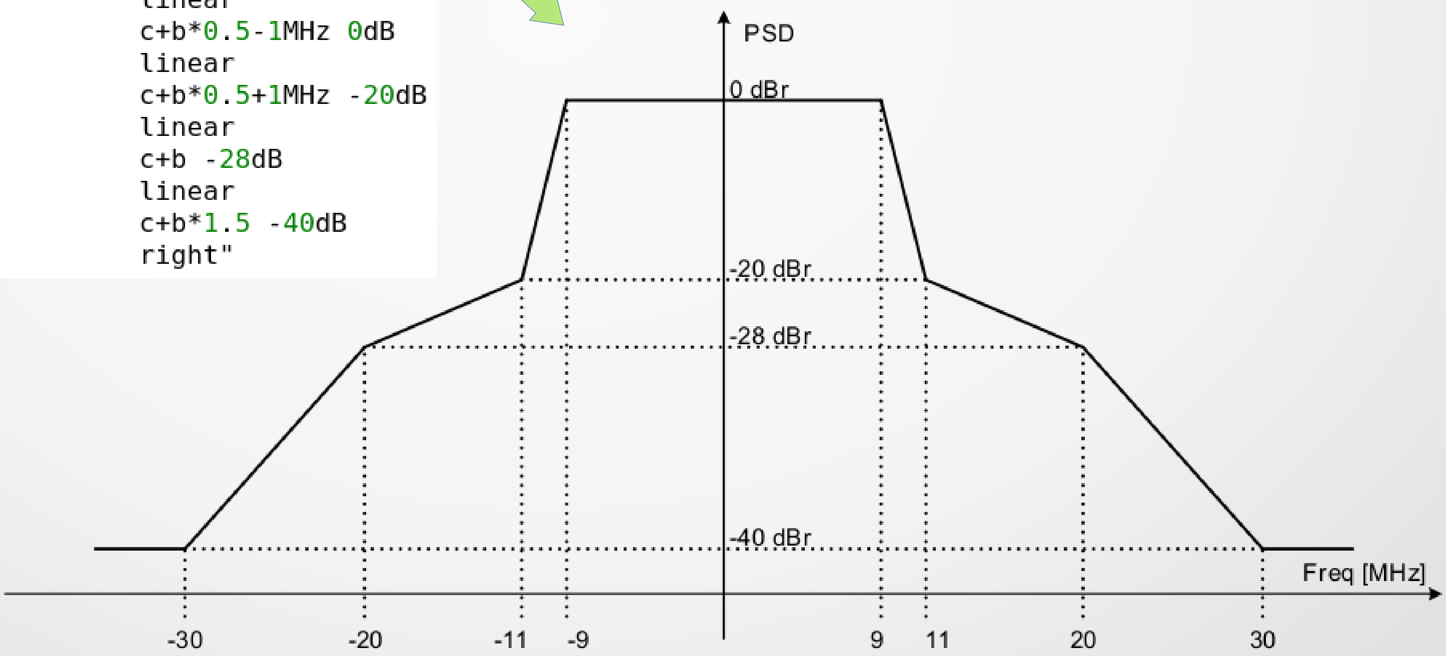
OFDM signal

- Represent arbitrary signal spectrum using interpolation

```
**.transmitter.frequencyGains = "left
                                 c-b*1.5 -40dB
                                 linear
                                 c-b -28dB
                                 linear
                                 c-b*0.5-1MHz -20dB
                                 linear
                                 c-b*0.5+1MHz 0dB
                                 linear
                                 c+b*0.5-1MHz 0dB
                                 linear
                                 c+b*0.5+1MHz -20dB
                                 linear
                                 c+b -28dB
                                 linear
                                 c+b*1.5 -40dB
                                 right"
```

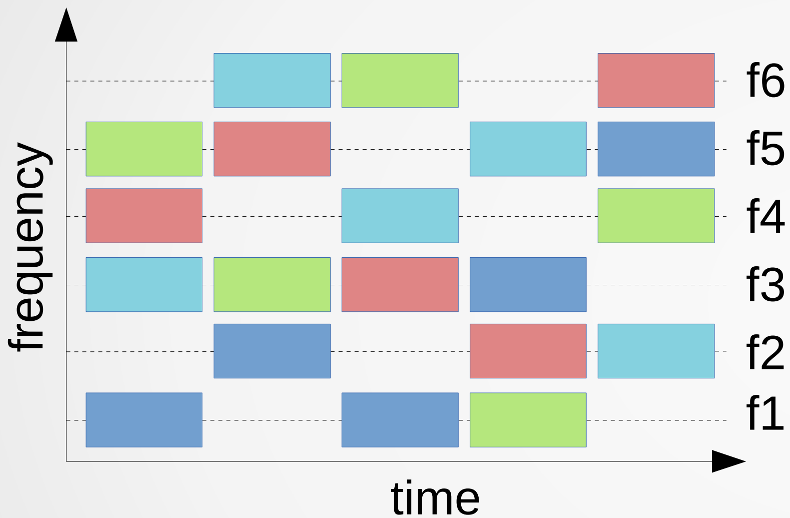
c = center frequency
b = bandwidth

left, linear = interpolation methods



FHSS signal

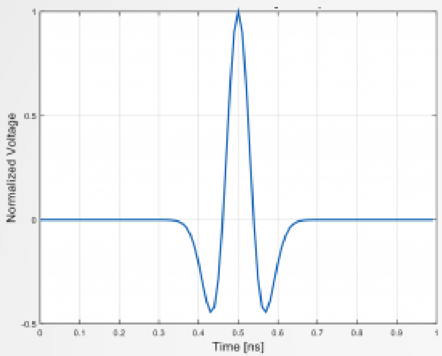
- Transmitted signal spreads both in time and frequency

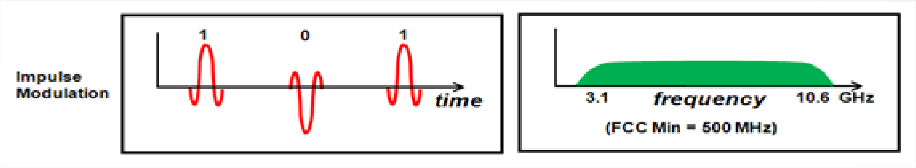


- SNIR is also represented in time and frequency domains
- Error models can vary from statistical to symbol level

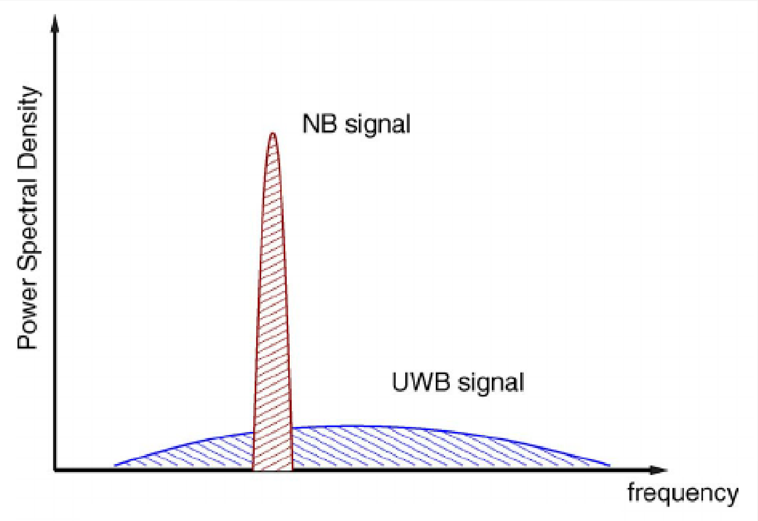
UWB signals

- Describe details of UWB signals in the time domain





- Compute path loss, interference and reception in the time domain



Multidimensional Mathematical Function API

```
template<typename R, typename D>
class INET_API IFunction : public IntrusivePtrCounter<IFunction<R, D>>
```

- `getRange(), getDomain()`
- `isFinite(Interval), isZero(Interval)`
- `getValue(Point), getIntegral(Interval)`
- `getMin(Interval), getMax(Interval), getMean(Interval)`
- `add(IFunction), subtract(IFunction)`
- `multiply(IFunction), divide(IFunction)`
- `print(Stream, Interval)`

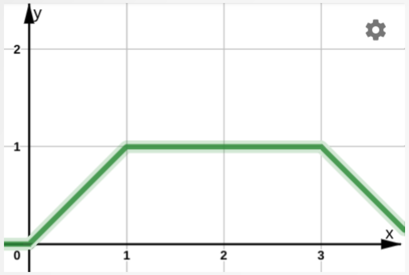
- **`partition(Interval, Callback)`**

Mathematical Function Properties

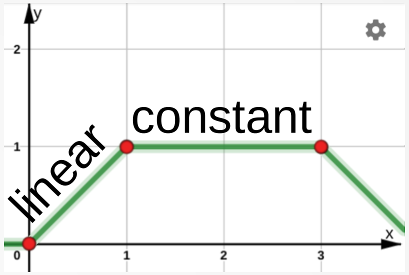
- Primitive and composite functions (one or more domain dimensions)
- Extensible implementation with user defined functions
- Use physical units (use C++ type system to ensure dimensional correctness; self documentation)
- Small objects (reduce memory footprint)
- Shared pointers (simplify memory management and sharing)
- Lazy computation (eliminate unused intermediate results)
- Optional caching (reuse results)

Partitioning to Primitive Functions I.

- Represent a function with piecewise primitive functions



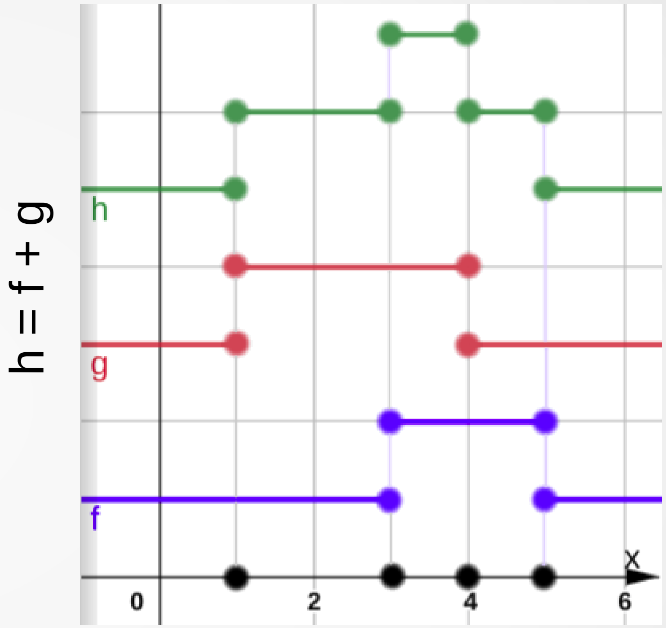
in one
dimension



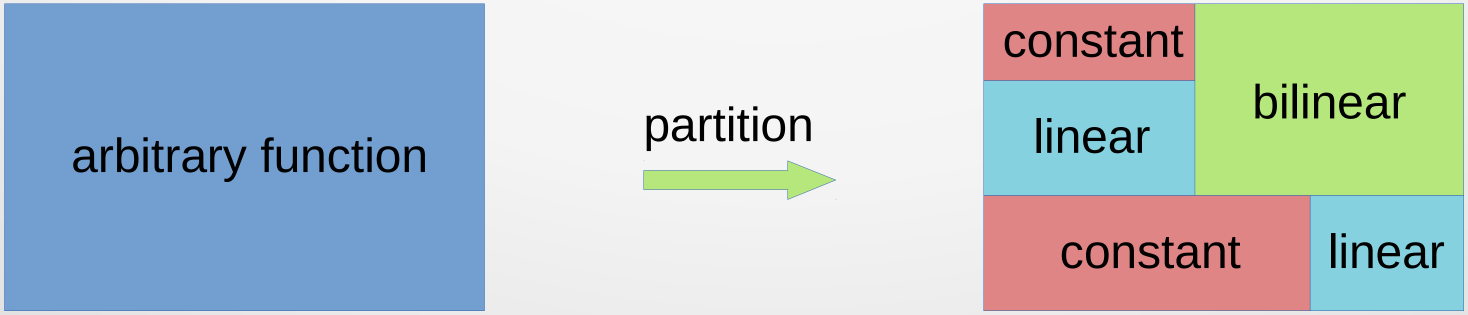
- Primitive mathematical functions:
  - Constant (over all dimensions)
  - Linear (in 1 dimension, constant in the others)
  - Bilinear (linear in 2 dimensions, constant in the others)
  - Reciprocal (in 1 dimension, constant in the others)

Partitioning to Primitive Functions II.

- Partitioning nested functions with subdivision



- Partitioning in 2 or more dimensions



Algebraic Operations I.

- Addition/subtraction (e.g. summing total interference)
  - constant ± constant = constant
  - linear ± constant = linear
  - linear ± linear = linear
  - reciprocal ± anything = *not supported*
  - etc.
- Multiplication (e.g. applying transmission power)
  - constant * constant = constant
  - constant * linear = linear
  - linear * linear = *not supported*
  - etc.

Algebraic Operations II.

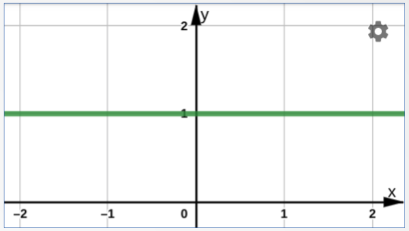
- Division (e.g. calculating SNIR)
  - constant / constant = constant
  - constant / linear = reciprocal
  - linear / constant = linear
  - linear / linear = reciprocal
  - reciprocal / reciprocal = *not supported*
  - Etc.
- Various additional algebraic optimizations for 0 and 1 constant values

Functions Operating on Functions

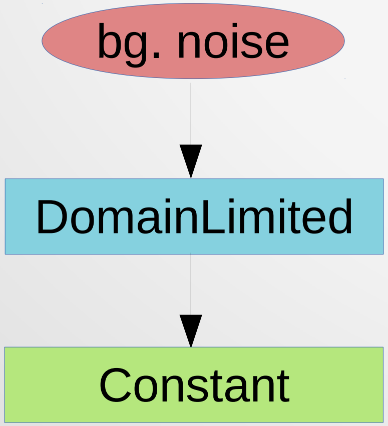
- **Shifting** along the domain axes (e.g. for applying transmission central frequency and start time to a signal)
- **Approximating** by sampling and using interpolation between samples (e.g. for using a frequency dependent attenuation function)
- **Integrating** over one dimension (reduces dimensions by 1; e.g. for computing the signal power over the spectrum)
- **Memoizing** (caching results to speed up further computations)

Isotropic Background Noise

```
template<typename R, typename D>
class INET_API ConstantFunction : public FunctionBase<R, D>
{
  protected:
    const R r;
```



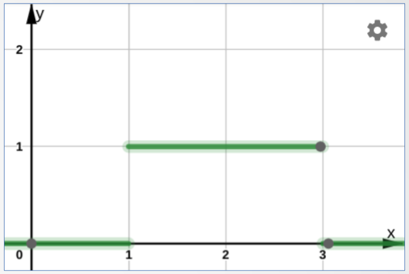

```
template<typename R, typename D>
class INET_API DomainLimitedFunction : public FunctionBase<R, D>
{
  protected:
    const Ptr<const IFunction<R, D>> f;
    const Interval<R> range;
    const typename D::I domain;
```



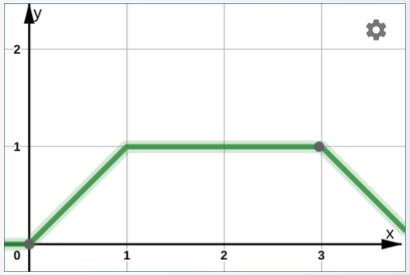

```
auto f = makeShared<ConstantFunction<WpHz, Domain<simsec, Hz>>>(p / b);
auto g = makeFirstQuadrantLimitedFunction(f);
```

Signal with Non-trivial Spectrum I.

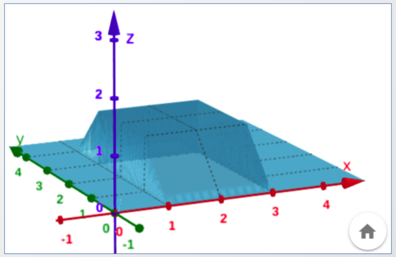
```
template<typename R, typename X>
class INET_API OneDimensionalBoxcarFunction : public FunctionBase<R, Domain<X>>
{
  protected:
    const X lower;
    const X upper;
    const R r;
```



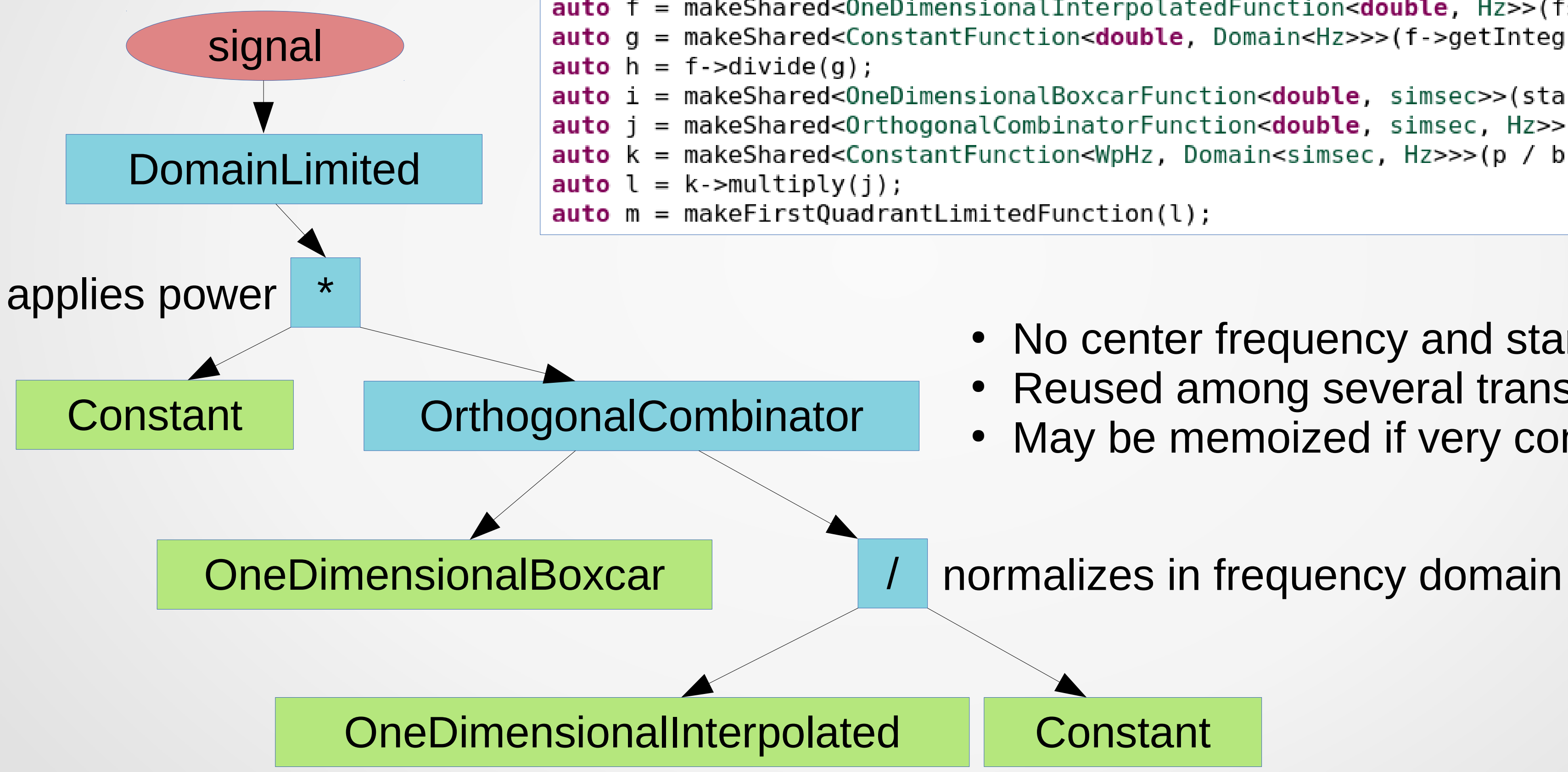

```
template<typename R, typename X>
class INET_API OneDimensionalInterpolatedFunction : public FunctionBase<R, Domain<X>>
{
  protected:
    const std::map<X, std::pair<R, const IInterpolator<X, R> *>> rs;
```




```
template<typename R, typename X, typename Y>
class INET_API OrthogonalCombinatorFunction : public FunctionBase<R, Domain<X, Y>>
{
  protected:
    const Ptr<const IFunction<R, Domain<X>>> f;
    const Ptr<const IFunction<double, Domain<Y>>> g;
```



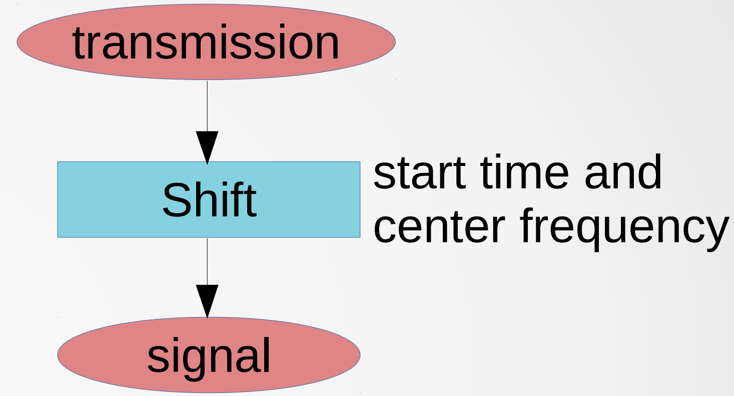
Signal with Non-trivial Spectrum II.




```
map<Hz, pair<double, const IInterpolator<Hz, double> *>> fs;
auto f = makeShared<OneDimensionalInterpolatedFunction<double, Hz>>(fs);
auto g = makeShared<ConstantFunction<double, Domain<Hz>>>(f->getIntegral());
auto h = f->divide(g);
auto i = makeShared<OneDimensionalBoxcarFunction<double, simsec>>(start, end, 1);
auto j = makeShared<OrthogonalCombinatorFunction<double, simsec, Hz>>(i, h);
auto k = makeShared<ConstantFunction<WpHz, Domain<simsec, Hz>>>(p / b);
auto l = k->multiply(j);
auto m = makeFirstQuadrantLimitedFunction(l);
```

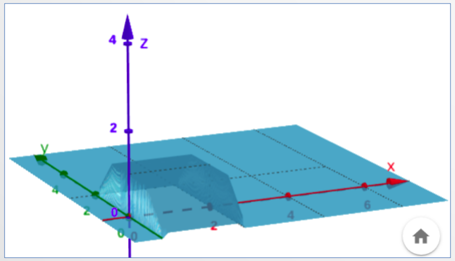
- No center frequency and start time
- Reused among several transmissions
- May be memoized if very complex

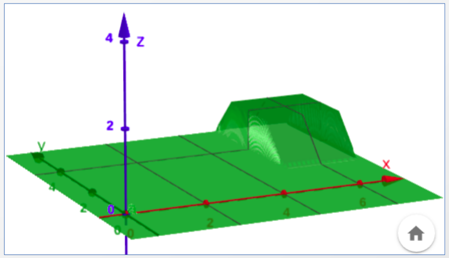
Signal Transmission




```
template<typename R, typename D>
class INET_API ShiftFunction : public FunctionBase<R, D>
{
  protected:
    const Ptr<const IFunction<R, D>> f;
    const typename D::P s;
```

```
auto shift = Point<simsec, Hz>(startTime, centerFrequency);
auto transmission = makeShared<ShiftFunction<WpHz, Domain<simsec, Hz>>>(signal, shift);
```

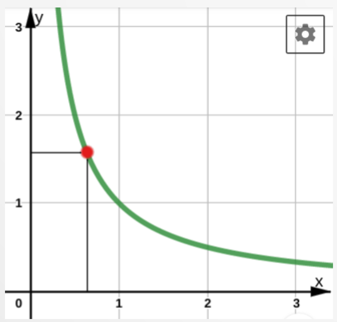


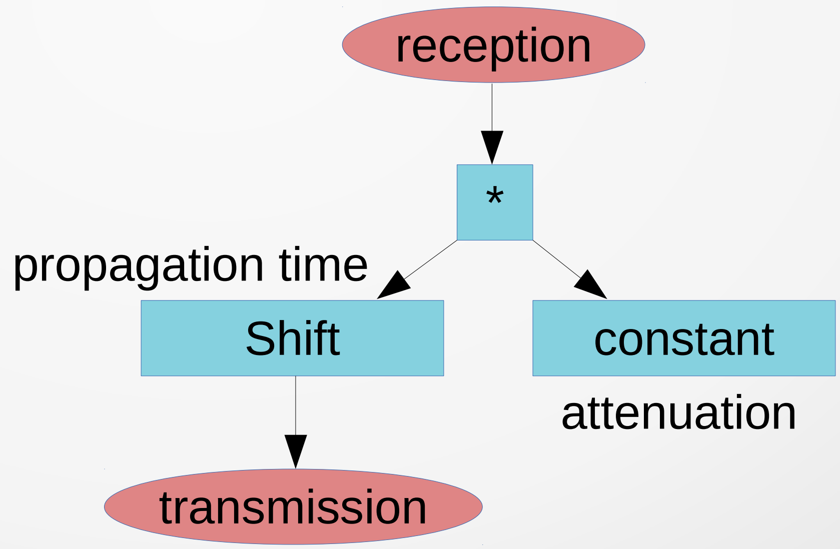


Reception with Constant Attenuation

```
auto shift = Point<simsec, Hz>(propagatonTime, 0);
auto f = makeShared<ShiftFunction<WpHz, Domain<simsec, Hz>>>(transmission, shift);
auto a = makeShared<FrequencyDependentAttenuationFunction>(tgain, rgain, tp, rp);
auto loss = a->getValue(Point<simsec, Hz>(0, cf));
auto c = makeShared<ConstantFunction<double, Domain<simsec, Hz>>>(loss);
auto reception = f->multiply(c);
```

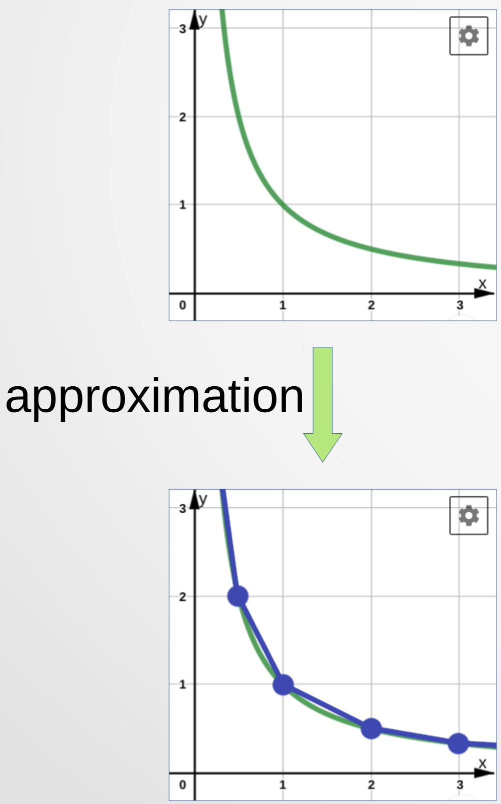
using the
center frequency

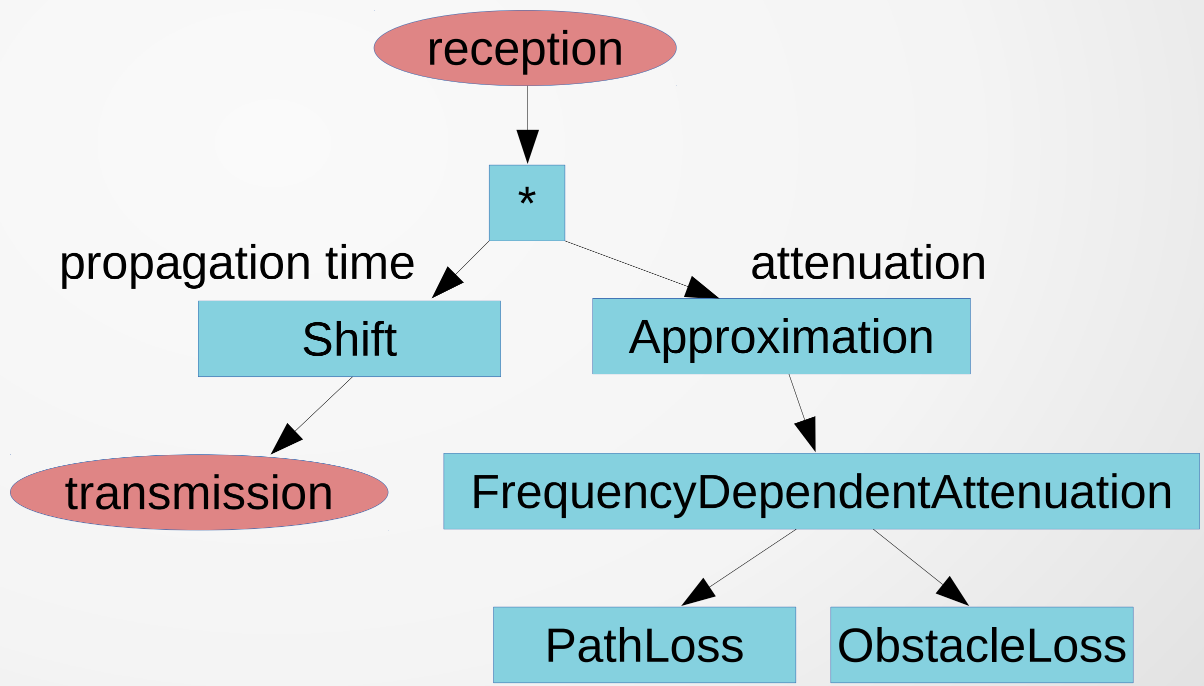




R. with Frequency Dependent Attenuation

```
auto shift = Point<simsec, Hz>(propagatonTime, 0);
auto f = makeShared<ShiftFunction<WpHz, Domain<simsec, Hz>>>(transmission, shift);
auto attenuation = makeShared<FrequencyDependentAttenuationFunction>(tgain, rgain, tp, rp);
auto g = makeShared<ApproximatedFunction<double, Domain<simsec, Hz>, 1, Hz>>(lower, upper, step,
                                                                              interpolator, attenuation);
auto reception = f->multiply(g);
```

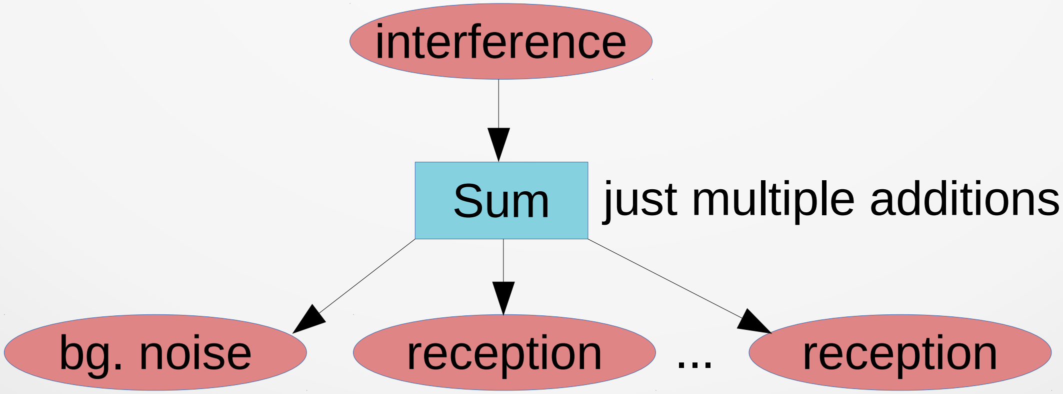




Interference

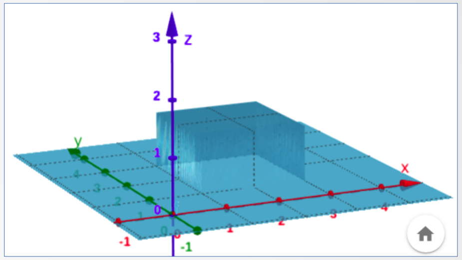
```
template<typename R, typename D>
class INET_API SumFunction : public FunctionBase<R, D>
{
  protected:
    std::vector<Ptr<const IFunction<R, D>>> fs;
```

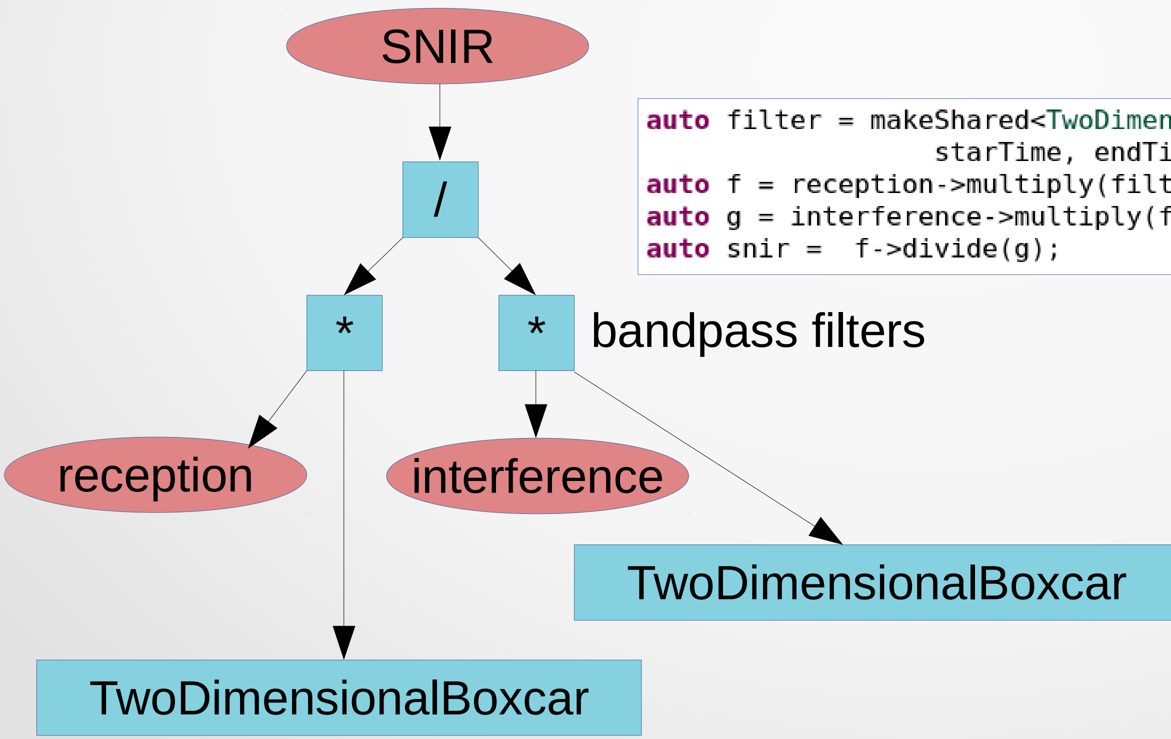
```
f = makeShared<SumFunction<WpHz, Domain<simsec, Hz>>>();
f->addElement(backgroundNoise);
for (auto reception : interferingReceptions)
    f->addElement(reception);
```



Signal to Noise and Interference Ratio

```
template<typename R, typename X, typename Y>
class INET_API TwoDimensionalBoxcarFunction : public FunctionBase<R, Domain<X, Y>>
{
  protected:
    const X lowerX;
    const X upperX;
    const Y lowerY;
    const Y upperY;
    const R r;
```





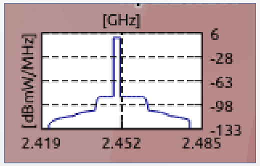

```
auto filter = makeShared<TwoDimensionalBoxcarFunction<double, simsec, Hz>>(
                  startTime, endTime, startFrequency, endFrequency, 1);
auto f = reception->multiply(filter);
auto g = interference->multiply(filter);
auto snir =  f->divide(g);
```

Transmission Medium Spectrum Visualization

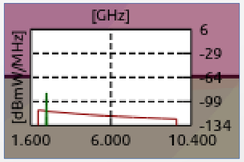
```
class INET_API PropagatedTransmissionPowerFunction : public FunctionBase<WpHz, Domain<m, m, m, simsec, Hz>>
{
  protected:
    const Ptr<const IFunction<WpHz, Domain<simsec, Hz>>> transmissionPowerFunction;
    const Point<m, m, m> startPosition;
    const mps propagationSpeed;
```

```
class INET_API SpaceAndFrequencyAttenuationFunction : public FunctionBase<double, Domain<m, m, m, simsec, Hz>>
{
  protected:
    const Ptr<const IFunction<double, Domain<Quaternion>>> transmitterAntennaGainFunction;
    const Ptr<const IFunction<double, Domain<mps, m, Hz>>> pathLossFunction;
    const Ptr<const IFunction<double, Domain<m, m, m, m, m, m, Hz>>> obstacleLossFunction;
    const Point<m, m, m> startPosition;
    const Quaternion startOrientation;
    const mps propagationSpeed;
```

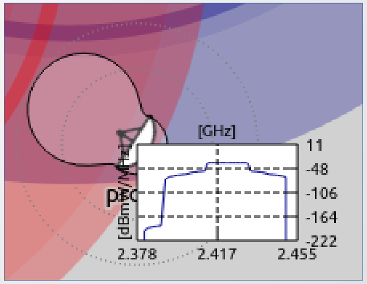
```
auto f = makeShared<PropagatedTransmissionPowerFunction>(transmission, position, speed);
auto attenuation = makeShared<SpaceAndFrequencyAttenuationFunction>(
                        antennaGain, pathLoss, obstacleLoss, position, orientation, speed);
auto g = makeShared<ApproximatedFunction<double, Domain<m, m, m, simsec, Hz>, 4, Hz>>(
             lower, upper, step, interpolator, attenuation);
auto receptionPowerFunction = f->multiply(g);
mediumPowerFunction->addElement(receptionPowerFunction);
```



WPAN and WIFI



WIFI and UWB



WIFI crosstalk

Using SNIR in the Error Model

- Using a single SNIR value for the whole signal

```
auto lower = Point<simsec, Hz>(startTime, centerFrequency - bandwidth / 2);
auto upper = Point<simsec, Hz>(endTime, centerFrequency + bandwidth / 2);
auto interval = Interval<simsec, Hz>(lower, upper, 0b11);
double min = snir->getMin(interval);
double mean = snir->getMean(interval);
```

  - Simple error models but less accurate
  - Problem with minimum SNIR: spike noise may cause reception failure
  - Problem with mean SNIR: substantial noise may doesn’t cause reception failure

- Using a single SNIR value for each physical layer symbol

```
for (auto time = startTime; time < endTime; time += symbolTime) {
    for (auto frequency = startFrequency; frequency < endFrequency; frequency += subcarrierBandwidth) {
        auto lower = Point<simsec, Hz>(time, frequency);
        auto upper = Point<simsec, Hz>(time + symbolTime, frequency + subcarrierBandwidth);
        auto interval = Interval<simsec, Hz>(lower, upper, 0b11);
        double min = snir->getMin(interval);
        double mean = snir->getMean(interval);
    }
}
```

  - More complicated error models but more accurate

Questions and Answers