generates a baseband signal comprising a series of chirps, that is then processed by the baseband demodulator 180, whose function is the reverse of that of the modulator 150, and provides a reconstructed digital signal 182.

[0015] As discussed in EP2449690, the modulator 150 synthesizes a baseband signal that comprises a series of chirps whose frequency changes, along a predetermined time interval, from an initial instantaneous value f_0 to a final instantaneous frequency f_1. It will be assumed, to simplify the description, that all the chirps have the same duration T, although this is not an absolute requirement for the invention.

[0016] The chirps in the baseband signal can be described by the time profile $f(t)$ of their instantaneous frequency or also by the function ϕ ~~(t)~~ defining the phase of the signal as a function of the time. Importantly, the modulator 150 can generate chirps having a plurality of different profiles, each corresponding to a symbol in a predetermined modulation alphabet.

[0017] According to an important feature of the invention, the modulator 150 can generate either *base chirp* ~~(also called *unmodulated chirps* in the following)~~ that have specific and predefined frequency profile, or one out of a set of possible *modulated chirps,* obtained from base chirps by time-shifting cyclically the base frequency profile. Figure 2a illustrates, by way of example, possible frequency and phase profiles of a base chirp and of one modulated chirps between the time instant $t = t_0$ at the beginning of a chirp and the instant $t = t_1$at the end of the chirp, while Figure 2b shows the corresponding baseband signals in the domain of time. The horizontal scale corresponds for example to a symbol and while the plots are represented as continuous, they will be represented by a finite number of discrete samples, in a concrete implementation. As to the vertical scales, they are normalized to the intended bandwidth or to the corresponding phase span. The phase, in particular, is represented in figure 2b as if it were an unbounded variable, in order to show better its

[0026] According to an aspect of the invention, transmitters and receiver nodes have preferably a communication mode that allow exchange of data by modulated chirp signals, and/or a ranging mode in which ranging exchange of signals takes place between a master device and a slave device that leads to the evaluation of the range between them. The slave is arranged for recognizing a ranging request and transmit back a ranging response containing chirps that precisely aligned in time and frequency with the chirps in the ranging requests, whereupon the master can receive the ranging response, analyze the time and frequency the chirps contained therein with respect to his own time reference, and estimate a range to the slave.

[0027] Figure 3 represents schematically a possible structure of a frame comprising a ranging request. The ranging requests starts with a preamble that may have a structure in common with other frames exchanged in the system of the invention for other purposes, and includes a detect sequence 411 of base ~~(i.e. un-modulated, or with cyclic shift equal to zero) symbols.~~symbols. The detect sequence 411 is used in the receiver to detect the beginning of the signal and, preferably, perform a first synchronisation of its time reference with the time reference in the transmitter. By dechirping the demodulated detect sequence , for example multiplying it by a locally-synthesized conjugate chirp, and performing a FFT operation, the receiver is able to determine a shift amount.

[0028] The length of the detect sequence can be arbitrarily long. This is used in application in which communications are sparse and separated by long intervals of inactivity during which the receivers are in low-power standby modes. The receiver exhibits in general an idle time, upon reception of a first signal, for commuting from the standby state into a fully awake state. The preamble is preferably chosen longer than the idle time of receivers, which ensures a high probability of preamble detection.

[0029] The end of the detect sequence is marked by one or more, preferably two, frame synchronisation symbols 412 that are chirps modulated with predetermined values, for example a first chirp with a

[0037] If the frequency synchronisation relies on the frequency synchronization symbols 413 only, some frequency offsets can result in an error of one modulation position: these are frequency offsets such that the demodulation of down-chirps give two identically likely values ~~(these are adjacent values).~~ A simple receiver is not able to discriminate the two values, and can take the wrong decision, yielding a small residual frequency offset, and half of a modulation position timing error. Such an error can give a full position modulation error, depending on noise. An alternative way to give better robustness to the receiver right after frequency synchronization is the reduced set of modulation values, at the expense of lower data rate.

[0038] In addition to performing fine time alignment, these symbols can give another fine frequency error estimate. This allows the implementation of simple coherent receivers, which in turn makes possible the modulation of the phase of symbols, in addition to cyclic shifts as modulation method.

[0039] The header part of the frame is a data field 415 that includes an indication that the frame is intended for ranging, and an identification code of the specific device whose ranging is needed. Only this specific device having an identification code equal to that specified in the header should respond to the ranging request.

[0040] The ranging symbols 416 are a succession of unmodulated chirps having a predetermined time structure. Preferably they are a succession of unmodulated chirps, i.e. base chirps.

[0041] Figure 6 illustrates schematically a possible sequence of steps in master and slave devices during a ranging exchange. The exchange is initiated by the master that transmits a ranging request ~~(step 201)~~ designating a particular slave device, and ~~then~~ waits ~~(step 230)~~ for the appropriate response. The slave receives the request ~~(step 300)~~ and deals with it as with a normal transmission at first. It runs usual steps of detection, time and frequency synchronization ~~(step 350),~~ and header decoding. Then it finds out that frame is a ranging request, and compares ~~(step 352)~~ the

ranging request ID to its own ID. If they match, it will proceed to next steps. During this first phase, the slave has estimated a frequency offset between master and itself. This frequency offset is used to compute ~~(step 356)~~ a timing drift between them, assuming timing and frequency derive from a same time reference. The slave then carries out the ranging specific steps:

[0042] a-Ranging synchronization ~~(step 357)~~:: this is to align in time to the ranging symbols transmitted by the master. Indeed, there can be a time offset right after the header, as the header is robust to small time offsets.

[0043] b-Ranging computation ~~(step 359)~~.: For each symbol, an adjusted dechirp operation is performed. A different local chirp is synthesized for dechirping each symbol in order to adjust for the timing drift: first the slope of the chirp is modified, by a very small fraction corresponding to the crystal offset. Second the starting frequency of the chirp is modified, to accommodate the accumulated timing error since the ranging synchronization instant, this value is equal to the symbol index times an evaluated timing drift per symbol. We here use fully the frequency-time equivalence of chirps, and the fact that these compensations are very small. In alternative, the receiver could interpolate over time, but this would be much more complex than a frequency shift. The compensations are small, frequency shifts of some PPMs won't make the signal step away from the channel. Frequency-time equivalence of chirps means that a time offset is equivalent, in certain aspects, to a frequency offset.

[0044] After FFT, the relative value of output at expected position ~~(bin 0, no modulation)~~ is compared to its neighbours. Then an interpolation is performed to find a fine timing ~~(step 362)~~.: This amounts to evaluating the frequency of a sinusoid from a discrete observation of FFT values not exactly placed on the desired frequency, and can be carried out in various ways.

[0045] Several symbols are averaged together to get the fine timing estimate. This allows the slave to determine the exact timing instant at which the response is to be transmitted by adding together the Coarse

Timing shift and the Fine Timing shift determined form the header ~~(step 350),~~ the duration of the ranging sequence given by the expression Ranging_symbols_numbers x ~~(symbol_duration+timing_drift_per_symbol)~~ and a predetermined ranging response offset. The slave thus waits until the timing instant ~~(step 364)~~ and transmits a ranging response ~~(step 367)~~.

[0046] The ranging response offset is a predetermined time interval that accommodates processing time, and uses the delay inside receive and transmit radios of the slave. Assuming the estimates are correct, the ranging response starting time of the signal at the antenna should equal the starting time of the received request, plus a fixed offset, preferably corresponding to an integer number of symbols. The ranging response offset can be constant or adaptively adjusted in order to compensate for temperature changes or other drift sources.

[0047] Importantly, by determining the coarse and fine time shift estimates and the timing drift, the slave device of the invention is capable to determine the time and frequency shifts of its own time reference with respect to that of the master, based on the time and frequency of chirps contained in the ranging request, thanks to the special property of the ranging request that includes chirp-modulated signals as explained above.

[0048] The ranging response is made of several unmodulated chirps. Preferably the same compensation is used than during the adjusted dechirp step 359 in ranging computation: a slope compensation, plus a timing drift accumulation compensation. This comes in addition to a compensation of transmitted frequency, according to estimated frequency. In this way, the ranging response is precisely aligned in time and frequency with the time reference of the master.

[0049] Here it is important to notice that the system is robust to small errors in frequency offset estimation. If a small error occurs, the receiving frequency and transmitted frequency will be slightly wrong, however the timing drift estimation will be almost correct. This is because timing drift estimation is the division of estimated frequency by carrier frequency. At

868MHz for instance, an error of 120 Hz, which is an unlikely error of a full FFT bin using a spreading factor of 4096 and a bandwidth of 500KHz, results in an error of only 0.13 ppm: this would give only a 1.5 metres ranging error. Second, as the response is time aligned to the request, if there is an error in estimated frequency, it will be compensated by a proportional error in time synchronization, such that the frequency = f(time) functions of received signal and demodulating signal are aligned. The impact of mis-synchronization is then only a tiny degradation of received energy.

[0050] These two effects are illustrated In figures 4a and 4b, that plot the instantaneous frequencies of a series of chirps in the master and in the slave. Chirps generated in the master device are represented by double lines, while those pertaining to the slave device are drawn by single lines. Solid lines indicate signal transmitted between master and slave, while dashed line stand for locally signals used for dechirping, for example:.

[0051] Figure 4a shows that the scheme is robust to small frequency estimation errors from the slave, Figure 4b shows that timing compensation is mandatory.

[0052] Returning now to figure 6, on the master side, the reception of ranging response ~~(step 231)~~ requires no synchronization steps. The master assumes that frequency and timing are perfectly aligned. The ranging response does not need to embed frequency estimation symbols. The master only estimates a timing, performing exactly the same steps ~~(236 and 240)~~ than the slave in ranging computation without compensation. This simplifies the modem, as the ranging core is common to both master and slave.

[0053] Preferably the invention comprises a diversity combining to improve the reliability and precision of range estimates. By diversity it is here intended that several ranging measures are performed between the same devices. These measures can be made successively with separated exchanges, in parallel during the same exchange, or both.

[0054] Preferably the combination of diversity is based on received signal strength indication. Measures that correspond to RSSIs which are lower than a given threshold are discarded. Then, remaining measures are averaged to get an initial range estimate. A weighted average of estimates, using RSSI in linear scale as weight, is also possible.

[0055] In a possible implementation, the threshold applied is around 6 dB: ranging measures which have an associated RSSI 6dB lower the maximum RSSI of the measures set are discarded. This threshold comes from experimental data.

[0056] If both spatial ~~(i.e antenna diversity)~~ and frequency diversity are used, the threshold is preferably computed for each antenna.

[0057] Once the average of selected measures is available, the range estimate is compensated for multipath. The average effect of multipath is to increase the measured time of flight compared to the single path, line of sight case. Since range is better represented by a measure of the direct path, this compensation is important. Since the system of the invention is in general incapable to resolve the temporal structure of the channel ~~(i.e. resolving individual echos)~~ because of its narrow band, proper compensation can improve considerably the reliability the range estimates.

[0058] The longer the distance between the devices, the greater the delay spread of the propagation channel. The impact of delay spread is however capped: echoes which occur after a delay longer than the time resolution of the system don't modify the range estimates.

[0059] At a very short distance, below a few meters, the power profile of the channel is decaying fast. We observed that the shorter the distance, the lower the impact of multipath. Actually for the limit case, which is null

[0065] The system of the invention is preferably arranged to auto-calibrate ranging measures, using distance dependent ranging error. As shown in Figure 5, the slope of estimated range versus distance increases as distance reduces, up to a slope of 5 for very close ranges, for example less than 15 metres. In a typical point to point application, the user is going to aim at a searched person or thing, at walking speed, thus it can be assumed that the rate of change of the true range is more or less constant and limited to, for example 1.5 m/s. Once there is a sudden change in the uncompensated range estimate ~~(before bias compensation described in 2),~~ and if the corresponding speed is too high to be pedestrian speed, the system can deduce that the true range to the searched object is less than 15 metres. This can be used to modify the calibration of the master device, to compensate for a calibration error of the master, or more likely of the slave ~~(searched device).~~ The modified calibration of the master actually improves the calibration of the pair. Conversely, If the range estimate is lower than 15 meters, but if at the same time the uncompensated distance estimate varies at a pedestrian speed, then the system can detect an error and increase the estimated distance, since for short distances estimations should vary faster. This automatic calibration only happens when devices are close, which is exactly when it is needed. Having this automatic calibration in which the rate of change of the estimated range is used as an indication of the true range improves confidence in the system, where devices can be let without ranging activity for long periods of time.

[0066] Thanks to the long range the system offers, the invention can operate in highly obstructed conditions. In these situations, the ranging estimate will still be almost as accurate, since it is based on time of flight measures. Then, comparing the range estimate to the average received signal strength, the invention can build and display an obstruction indication. One way to compute this indication is to first compute a path loss exponent, which should be equal to 2 in line of sight. Path loss exponent is such that the receive power is inversely proportional to the distance raised to the power of the exponent. For this a knowledge of the transmitted power is needed, but this information does not need to be highly accurate, since the obstructions effect is usually dominant. A possible

Claims

1. A system comprising at least a transmitting device and a receiving device, each device comprising a time reference and being arranged for transmitting and receiving radio signals that include a plurality of chirps, wherein each chirp is limited in time between an initial instant ~~$(T_0)_{TL}$~~ at which the signal has ~~an~~ initial instantaneous frequency ~~(f_0)~~ and a final instant ~~(T_1)~~ at which the signal has a final instantaneous frequency ~~$(f_1)_{TL}$~~ said initial and final instants and said initial and final frequencies being determined by the time reference, said devices having a ranging mode, in which a ranging request is transmitted ~~(201)~~ from the transmitting device to the receiving device, and wherein the receiving device is arranged for receiving ~~(300)~~ the ranging request and for determining the time and frequency shifts of the time reference of the receiving device with respect to the time reference of the transmitting device ~~(350, 359, 362)$_{TL}$~~ based on the time and frequency of chirps contained in the ranging request.

2. The system of the previous claim, further arranged for estimating a range to the receiving device ~~(B)~~ based on the time and frequency of chirps contained in the ranging response, wherein the ranging response is separated from the ranging request by a delay whose length is determined by a secret shared by the transmitting device ~~(A)~~ and the receiving device ~~(B)~~.

3. The system of one of claims 1 or 2, further comprising a plurality of receiving devices ~~(521-524)~~ having a common time reference arranged for receiving the ranging request, and for determining a plurality of time offsets dependent on the range between the transmitting device and each receiving device, and a computing means ~~$(560)_{TL}$~~ arranged for determining the position of the transmitting device based on said time offsets.

4. The system of one of claims 1 or 2, comprising a plurality of transmitting devices ~~(521-524)~~ having a common time reference arranged for transmitting said ranging requests, and a receiving device, arranged for

arranged for receiving the ranging requests and for a plurality of time offsets dependent on the range between the receiving device and each transmitting device, and for determining the position of the receiving device based on said time offsets.

5. The system of any one of the previous ~~claim~~claims, having a open ranging mode in which the delay ~~(424)~~ of the ranging reply is predetermined.

6. The system of any one of the previous claims, wherein each chirp is limited in time between an initial instant ~~$(T_0)_i$~~ at which the signal has an initial instantaneous frequency ~~(f_0)~~ and an initial phase ~~$(\phi_0)_i$~~ and a final instant ~~(T_1)~~ at which the signal has a final instantaneous ~~frequency~~ ~~(f_1)~~ ~~and~~frequency and a final phase ~~$(\phi_1)_i$~~ the phase of the signal being essentially continuous.

7. The system of any one of the previous claims, wherein the ranging request comprises a series of identical chirps, and the receiving device is arranged for performing a dechirp operation, in which each received chirp is multiplied by a locally-generated conjugate chirp, and a FFT is executed on the result, whereupon the peak of the FFT is an indication of the time shift between the received chirps and the locally generated ones.

8. The system of the previous claim, wherein the receiving device is arranged for performing an adjusted dechirp, in which a different locally-generated chirp is used at each received chirp in order to adjust for the timing and frequency shifts.

9. The system of any one of the previous claims, wherein the ranging response comprises a series of identical chirps that are synthesized in the receiving device applying different parameters to each chirp, such that they are aligned in time and frequency with the time reference of the transmitting device.

10. The system of any one of the previous claims, wherein the receiving and/or the transmitting devices are arranged to perform several ranging measures and for combining them based on the associated signal strength.

11. The system of any one of the previous claims, wherein the frequency and/or the bandwidth and/or the spreading factor of the radio signals is adapted based on the channel state.

12. The system of any one of the previous claims, wherein the receiving device is arranged to compensate a range estimate affected by multipath by applying a compensation curve.

13. The system of the previous claim, arranged to execute automatic calibration of the compensation curve, in which the rate of change of the estimated range is used as an indication of the true range.

14. The system of any one of the previous claims, further arranged to computed an obstruction indication based on the range estimate and the received signal strength.

15. The system of any one of the previous claims, wherein the transmitting device and the receiving device have a communication mode that allows them to exchange digital data by chirp-modulated radio signals.