Pulsed ALOHA - a Form of Multiaccess UWB Communications

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Abstract - Pulsed ALOHA is a form of impulse Ultra-Wideband communication where a bit is carried with each pulse, rather than using a time spreading code. Pulsed ALOHA and Wideband ALOHA are perfect fits to low energy wide-bandwidth communication. They permit energy-efficient higher data rates. Pulsed ALOHA has some unique advantages in collision avoidance and collision tolerance over Wideband ALOHA, when used with multi-receiver diversity reception. Both systems have substantial advantages in rate, energy efficiency, and simplicity over using spreading codes. A one-dimensional network example is given, which could be a model for a system along auto roadways.

Index terms - ALOHA, ultra-wideband impulse radio modulation, multiaccess communication, carrier sense multiaccess, antenna arrays, road transportation communication.

I. INTRODUCTION

Direct-sequence CDMA is a popular wireless multiaccess system. Its operations are quite complex, however, since each sender must be assigned a separate code and the base station must be able to correlate with each code. Also, because a bit must be carried by perhaps a hundred pulses, the data rate per sender using one code sequence is low relative to the transmitted pulse rate 1/T. Also, careful power control is needed for good performance.

The idea for Pulsed ALOHA originated from a suggestion by Abramson [1] that CDMA could be operated with everyone using the same code - called Spread ALOHA. After correlation with the common code pattern, two senders would produce in most cases two pulse trains that do not overlap. The advantage is having just one code for everyone, which is simpler.

In Spread ALOHA, narrow pulse transmission is not used. The possibility of getting the same effect using no spreading code at all, and essentially no correlator, by sending narrow pulses, was suggested by the author in [2]. Call this **Pulsed ALOHA**. This did not seem practical at the time, because it required high peak-to-average power ratio, which designers generally sought to avoid. But ultra-wideband pulse transmission [3-22] shows that high peak-to-average power ratio is practical.

In Pulsed ALOHA, one bit is sent by a pulse of short duration τ, each T seconds. Normally, τ/T would be small, < 0.01. A limitation of Pulsed ALOHA is that occasionally pulse trains do overlap. This is similar to the ALOHA event that packets collide. With low τ/T this event is rare in low traffic. Also, multi-receiver reception can greatly reduce this effect.

UWB design has been divided into two categories: impulse-based, IUWB, and multicarrier-based, MCUWB, [6]. Pulsed ALOHA is in the IUWB category. The systems proposed for IUWB multiaccess communication mainly employ spreading codes [6-14], where one bit is sent in LT seconds, by a sequence of L narrow pulses of duration τ, one pulse per T seconds, with pulse polarity, amplitude or pulse position varied by a spreading code. In [14] a variable spreading length is proposed. Often L is 100 or more. However, Pulsed ALOHA need not use a spreading code; it could send one bit per pulse, L times the rate of a spread system. A spreading code could be used as a preamble, to simplify detection. This code could be the same for all senders.

Another option is to send more than one bit per pulse. A related method is light-traffic Wideband ALOHA [1]. In light-traffic wideband ALOHA, a full packet of data is sent at a very high rate, given that collisions are rare. However, we will see that Pulsed ALOHA has some multi-receiver interference reduction features not available to Wideband ALOHA.

There are two different cases involving multiaccess. Case one is where senders are sending to a common base station or network of base stations, and the receiver or cooperating receivers wish to decode all senders. Case two is where different senders are sending to different, independent receivers. The main emphasis here is on case one, though some of the ideas have relevance for case two. In case one, if two senders interfere, there is some gain if one can be decoded, such as due to the capture effect.[23-31]. In case two, capture doesn't help at a receiver that needs only to decode the weaker signal, except if it is able to decode the unwanted signal and subtract its effect.

Feedback is essential for reliability in ALOHA systems. With a common base station network, feedback is naturally available for control purposes, such as power control and scheduling. Thus acknowledgment is not an excessive burden. Time delay is important for some traffic, but priorities and feedback control can keep retransmission a minimum for this class.

If channel sensing is available, a Pulsed ALOHA sender could time new data transmissions to minimize the chance of interference with an ongoing transmission. There are some difficulties in sensing an active pulse transmission, because individual pulses are quite weak. References [20,21] show efficient methods for sensing.

II. MULTIPLE RECEIVER BENEFITS.

A. Different multiple sender timings at different, cooperating receiving points.

Suppose two senders' pulses collide at a receiving point. At another receiving point at a different location, their pulse trains will almost always be separated, because at the speed of light a 1 nanosecond delay change, often enough to separate the pulse trains, corresponds to only a 0.3 meter distance change. This is illustrated in Figure 1, where senders A and B are received both at point 1 and point 2. Decoding of both can be done at point 2. The only case where they might not be separated at point 2 is if the distance, d, between them is so small that the propagation time for distance d is not much more than the time difference needed for separation.

Wideband ALOHA does not have this feature. In wideband ALOHA, data packets are a large multiple of τ in duration, so that collisions at point 1 in most cases would be collisions at point 2 as well. However, with the capture effect, ALOHA has the feature that one of two interferers might be much stronger at point 1, while the other is much stronger at point 2. Again, by cooperation between points 1 and 2, both could be decoded.

Actual pulse receptions are more spread in time than the transmitted pulse owing to multipath effects [5,10,21]. However, estimates of the channel impulse response can allow separation of the pulses despite some overlap .

B. Directionality factors.

A carrierless pulse does not provide phase carrier additions for directional antennas, although directional antennas are possible for UWB [15,16] . However, multiple receiving antenna elements have direction-of-arrival features that can be used to give multiple opportunities for non-collision and enhanced decoding. Multiple antennas for UWB are described in [17-19]. However, the usage to be described here is different.

Consider an antenna with 8 equally-spaced elements, as in Figure 2. If the sender is at a distance large compared to the element spacing, arrivals can be represented by parallel lines. The signal arrives with time differences $0, \Delta t, 2\Delta t,,,,,,,7\Delta t$ relative to the closest element. Basically we have eight identical pulse trains, each precisely separated by Δt from its neighbor. The value Δt can be learned readily through correlation with the identical pulse streams. Signals from other directions will give eight outputs with a different time spacing. For sufficiently large element spacing, the other signal can overlap at all eight outputs (ideally) only if it came from approximately the same direction and happened to be in near-synchronism as well. The 8 direct path responses to the desired signal are perfectly correlated after time adjustments; the data itself takes on somewhat the role of a code pattern. If one of the 8 receptions achieve separation, that could be enough, or correlation among the receptions could reinforce the correctly-timed signals relative to the signal from a different direction.

A second desired signal arriving from a different direction would have a different $\Delta t'$, and could be separately correlated with a different $\Delta t'$ adjustment.

It is extremely rare that two senders will choose both the same starting position in the cycle and also a starting bit just a few bits apart. First there is the probability p that some other sender sends its pulse train at an interfering point in the T-second cycle, and then, given the two N-bit packets collide in this way, the probability that the two will start within k T-second cycles of each other is k/N. If k bits is enough to lock onto the preamble and find the Δt, it could form the proper close correlations between the 8 received antenna signals, which would ease the task of decoding the packet which started first. The probability this wouldn't happen is about pk/N.

If there are significant multipath contributions, portions of the desired signal arriving over less direct paths can have different Δt, but we can pick a Δt that correlates in the main component.

There is a wide choice of number of elements and spacing. More elements allow more chances for decoding. Δt_{max} is the propagation time directly between adjacent elements, and T is the period between a sender's pulses.

With ideal received pulses corresponding to what is transmitted, we would like to say that if the pulse width is τ, pulses with separation τ or greater would not overlap. However, with multipath propagation, as with indoor applications, multipath creates a response far longer than τ [16]. Basically, the response has many impulse components, one corresponding to each path, though the direct path usually is strongest and is the first received.

Since UWB signal ranges often are short to limit radiated power, the assumption of parallel arriving paths can be questionable. The property of different spacings from different directions would remain valid, but the adjacent delay differences would no longer be equal.

C. A two-dimensional pattern

Suppose a potential interferer arrives at an angle θ_2 which is close to the angle θ defined in Figure 2. Continue to assume parallel arrival lines, with range much greater than element spacing, although this is questionable for some applications.

$$\Delta t_2 - \Delta t = \Delta t_{max} \cdot [\cos\theta_2 - \cos\theta]$$
$$\frac{\partial(\Delta t_2 - \Delta t)}{\partial\theta_2} = -\Delta t_{max} \cdot \sin\theta_2 \qquad (1)$$

Thus the worst sensitivity is at $\theta = 0$, where the signals arrive in line with the antenna elements, and the best is at $\theta = 90°$. This suggests using a two-dimensional array to smooth sensitivity over different angles. Figure 3 shows such an array with 8 elements. The Δt's are defined horizontally left to right and vertically down to up.

Corresponding to (1), the sensitivity to arrival angle for the horizontal component is $\Delta t_{max} \cos \theta_2$. The maximum of the two sensitivities is

$$\Delta t_{max} \cdot \max\{|\cos\theta|, |\sin\theta|\} \geq \Delta t_{max} \cdot \frac{1}{\sqrt{2}} \qquad (2)$$

The Δt_v learned can determine Δt_h through the common θ. The difference between the lower left and bottom reference times is, from Figure 3b,

$$\Delta t_{45} = \sqrt{2} \cdot \frac{3}{2} \Delta t_{max} \sin(45 - \theta) \qquad (3)$$

Thus one Δt measurement horizontally or vertically determines all time differences of the desired signal. Of course multiple measurements can be made to confirm accuracy.

In combining signals from the antennas there are two possibly conflicting factors. An interfering signal coming from about the same direction and closely matched in pulse time is hard to separate if the desired signal is arriving in the least sensitive direction. But the self-correlation of the desired signal at different elements is easier to do with multipath if the desired signal is arriving in the least sensitive direction, because the relative timing of the main multipath arrivals would be more consistent. Thus combining of the multipath desired signal is most effective from the least sensitive direction, while separation of a close arrival angle interferer is most effective from the most sensitive direction. These factors could be taken into account in doing the combining.

Choice of element spacing. Let τ be the pulse width, and assume $m\tau$ is the minimum pulse spacing to have no interference. With no multipath, and ideal pulse response, m could be as small as 1, but with multipath it could be many times larger. Correlation with an approximately known impulse response can reduce the value of m. If two senders interfere exactly at one element, we desire that they be separated by at least $m\tau$ at some other element.

The choice of spacing affects the range of arrival angle ($\pm \Delta\theta_m$) where the interfering signal cannot be separated. For the 8 - element, two-dimensional case, we need

$(\Delta\theta_m)\cdot(.7071\cdot 2\Delta t_{max}) > m\tau.$ (4)

Equation (4) applies because the coincident point is at least $2\Delta t_{max}$ away from some end point in the maximum sensitivity (horizontal or vertical) direction.

For m = 2 and a range of ±0.2 radian or ± 11.44°, we find $2\Delta t_{max} > 14.1\tau$. At $\tau = 0.2$ nanoseconds, $2\Delta t_{max} = 2.82$ nanoseconds. The end-to-end spacing ($3\Delta t_{max}$) in a dimension would be 1.27 meters. In environments with larger multipath spread, the minimum pulse spacing might have to be larger, and then the array size might have to be larger. Also, in the 1-10 meter range the arrival lines from a source would not be close to parallel.

With short ranges and/or multipath, the numbers don't favor getting complete separation of overlapping signals. However, if the Δt's of the desired signal are known, the components from the n elements can be perfectly correlated with each other, whereas another signal from a different direction would not correlate well for the time shifts used.

Multi-element correlation. In direct sequence CDMA, correlation with the direct sequence L-chip pattern for one bit creates an L-dimensional correlation for one bit relative to interference. Correlation with the multi-element receptions, with proper adjustments for the time differences, has a similar effect for one bit. Thus an n-element antenna and a k-bit preamble provides nk dimensions of correlation for time difference and impulse response estimation.

D. Other factors

Suppose the desired signal and another signal, that happen to be to close in timing, also have arrival angles that are too close for interference separation. There are several options.

1) The receiving station could command one of the senders to shift its reference time.

2) A communicator that fails to get acknowledged could retry at a different reference time. This could be a general rule.

3) Usually one of the senders will start its packet first. This allows better learning of the first

sender’s pulse response shape and amplitude, so a close spacing might be overcome.

4) Senders at about the same angle are likely to be close to one another. If they sense the other’s transmission they could select a different starting time. This is especially true for the sender that would start later.

5) With multiple receptions for each bit, a decoder can make its decision based on combining all element receptions adjusted for known Δt_h, Δt_v. Some element receptions judged less reliable can be erased prior to combination, or there can be a weighted log likelihood decision for each bit.

6) By chance, the interfering signal might be considerably weaker than the desired signal, which might make it possible to decode the desired signal despite the interference. Or the impulse response of the two signals could be so different that they could be separated readily by correlators.

III. USE OF A MULTI-BASE NETWORK.

In ordinary cellular communication, a mobile station at any given time belongs to the cell of a particular base station controlled by it. Its slot position (TDM) or its code (CDMA) is assigned by the base station, and its power of transmission is controlled by the base station. As it moves to another cell it is handed off to another base station and given a new cell and usually a new code. With multiple base stations in relatively close proximity, the most favored base station changes rapidly, perhaps faster than could be followed by a handoff strategy. Instead, consider a number of base stations tied together with a high speed, normally wired, network. This idea was proposed in [32]. The base stations are presumed capable of recognizing duplicates, and will forward and acknowledge just one copy of a successful packet. This network may have a central control station or may use distributed control. With fading and the capture effect, such schemes are capable of high throughput [33,34]. The base stations act as a sort of diversity reception for all the sending mobiles. Recently, a distributed wireless communication system has been proposed [35] based on a dense network of base stations and antennas.

What has been referred to as a “base station” actually can have a set of antenna systems that all send their results to that processing base station. That is, there can be a two-level hierarchy of base stations - antenna systems and processing base stations that compute, intercommunicate and decide at a higher level. An example of this is shown in Figure 4. The dark circles, denoted for example as A, B, and C, are processing base stations, connected via the base station network. The smaller circle points, for example x and y, represent antennas. The triangles represent mobile senders.

If the senders use Pulsed ALOHA, the pulse trains of mobiles m_1 and m_2 might collide in time at D, but not at E. Also, m_2 might be received interference-free at C, because m_1 is out of range.

If they use Wideband ALOHA, sending multi-bit packets in a burst, they are likely to collide at both D and E because their length is many pulse durations, but m_1 is much stronger than m_2 at E, and m_1 will likely succeed by the capture effect, while m_2 will succeed at C.

IV. NUMBER OF SIMULTANEOUS USERS IN A PULSED ALOHA MULTI-BASE NETWORK.

As we saw in Section II, the multi-element antenna array might not have sufficient spacing between elements to separate colliding signals at short ranges. With a multibase network, however, spacings can be greatly different at different receiving points, as illustrated in Figure 1. Suppose there are n randomly-placed other senders, and at a particular receiving site the probability is $p = m\tau/T$ that a specific desired signal is overlapped by a particular other signal. Since the data rate of the sender is R = 1/T bits/second ignoring preamble overhead, we can rewrite this as

$$p = m\tau R. \qquad (5)$$

Also, assume that the chances of this happening at each of b base network sites is independent of it happening at the other sites. Again, this is not true if the senders are extremely close to each other; i.e. a few nanoseconds of propagation apart. However, as mentioned in Section II.D, carrier sensing could be used to eliminate interference at such close ranges.

$$P_{free} = P(\text{a reception is not interfered with}) = (1- p)^n; \qquad (6)$$

$$P(\text{all receptions interfered with}) = (1- P_{free})^b \qquad (7)$$

Equation 7 is plotted in Figure 5 for p = 0.05. With τ = 0.2 nanoseconds, m = 2, this implies 125 megabits/second per sender. Or with m = 10, 25 megabits/sender. With 7 interferers and 6 receivers, the chance of no clean reception anywhere is about 10^{-3}.

It is possible to have senders using various rates, with basic periods an integer multiple of some smallest T. For example, if the desired sender was sending at period T, but the others at period 4T, an interfering sender at an element x would at worst erase 1/4 of the bits, and a different interfering sender at a different element y would erase 1/4 of the bits, but if they erased different bits, the desired signal could have at least one reliable copy of every bit from x or y, as exemplified in the following

(e = erased):

x	dddedddedddedddedddedddeddde
y	dedddedddedddedddedddedddedd
combined	dddddddddddddddddddddddddddd

V. POWER CONTROL, ENERGY USAGE AND WIDEBAND ALOHA.

CDMA systems use power control on the uplink of a base station network, so as to give all senders about the same protection against multi-user interference. Note that in pulsed ALOHA or wideband ALOHA there is no need that signals be received at about the same power level if they don't overlap. Even if they overlap, a higher power signal will hardly be affected by a significantly lower power signal. There is also the possibility of decoding both overlapping signals by subtracting out the effects of a decoded stronger signal.

Ultra-wideband communication is best adapted to low power short-range communication. The number of simultaneous users is thus fairly small. Also, since collisions are rare, very little energy is needed to overcome multiuser interference. In general, light traffic Pulsed ALOHA or Wideband ALOHA can send at very high data rates with rare collisions, and thus minimal energy/bit operation.

In sending one pulse per bit instead of 100 pulses per bit as in discrete sequence UWB, the pulses could have 10 times the amplitude for the same energy per bit. In Pulsed ALOHA data would be sent at 100 times the rate of a single discrete sequence UWB transmission. For strictly noise-limited capacity, 100 times the data rate requires 100 times the average power. Discrete sequence UWB would need 100 simultaneous senders to match the one-sender Pulsed ALOHA data rate. This would create a great deal of interference, due to imperfect orthogonality, that would require additional power to overcome. The full-bit pulses of Pulsed ALOHA would not have this interference to overcome, so most likely would not have to be as large as 10 times the amplitude of the discrete code sequence method. Power control at the transmitter would need to be limited only by FCC regulations and the sender's energy constraints. For high rate single users, the Pulsed ALOHA could increase its rate by a factor N by reducing T to T/N such that the pulses were spaced as closely as separability and power constraints could allow. In a receiver-controlled system, a sender could be assigned a value of N, an integer ≥ 1, according to traffic conditions. Since ALOHA systems require acknowledgment, a receiver could refuse to accept data at rates exceeding its assignment.

Wideband Aloha or extension of Pulsed ALOHA to a T/N comparable to pulse rate has an attractive feature of allowing extremely high data rates for an individual sender when there are no other senders. Such a sender, given sufficient power, could send continuously at many gigabits/second in a band of several gigaherz. However, other senders may come along, so you don't want to allow this unconditionally. Since ALOHA requires feedback acknowledgment, such senders could be controlled by specifying maximum packet size and requiring stop-and-wait transmission, incorporating "receiver not ready", "data refused" or waiting time to next packet or window commands in the acknowledgment signal. This could allow a sender to communicate steadily at high rates while channel usage and regulation permit. The controls available with stop-and-wait transmission can also act to stabilize the multiaccess network. Specification of an exact waiting time to next sending could actually allow avoidance of collision with new sender packets.

Bunching of data pulses in Wideband AlOHA can interfere with the ability to easily differentiate multiple paths of a signal, making fading more of a problem than with Pulsed ALOHA.

VI. A ONE-DIMENSIONAL EXAMPLE.

It is interesting to look at a case of a one-dimensional spatial network. Also, it is related to the important case of mobile communication from an automobile traveling on a road. The multibase method could perhaps encompass a whole network of major highways.

Figure 6 illustrates a one-dimensional network of base stations and antennas. Let A, B, C, D,....represent base stations. Station A has antennas j,k,l, and each station has 3 antennas as indicated. Say a mobile can be heard by two antennas to the right and two to the left. Thus, a mobile situated between k and l may be heard by j, k, and l of A, and by m of B. A has 3 possibilities to correctly decode individually, or by combining 2 or 3 receptions. Also B has a possibility to decode. If neither A nor B could decode separately, they could combine their decisions with a possibility of success. If they both decode successfully, it could be recognized that A had the stronger reception and should send the acknowledgment. Due to the physical location and use of low power it is unlikely more than two adjacent stations would decode the same packet successfully in this example. The ratio of base stations to antennas is flexible according to how the processing tasks are shared and other factors. Assume for the example that the antennas are equally spaced.

The effect of motion on a particular packet is negligible. At a 50 megabit per second data rate, a 1000-bit packet is transmitted in $2 \cdot 10^{-5}$ seconds. At 100 km/hr, an automobile would travel 0.0556 centimeters, which would change the propagation time delay of the last bit by 0.0019 nanoseconds relative to the first bit.

A. Some simple quantitative relations.

Assume all senders are sending at the same rate, one bit per T seconds.

Let

d_A = antenna separation in meters;

Range = $\pm kd_A$

ρ = average number of active senders/meter in a given time period T;

R = average total data transfer rate in bits/second per meter, assuming all transmissions are successful.

$R = \rho / T.$ (8)

α = the fraction of the period T for which significant pulse energy is are being received.

$m\tau$ = effective duration of a received pulse with transmitted duration τ.

The average number of senders in range of a given receiver is $2kd_A\rho$. They will be transmitting an average of $2kd_A\rho$ bits per T seconds to the receiver. These will occupy $2kd_A\rho m\tau$ of the T seconds, assuming there is no overlap. Thus,

$\alpha = 2kd_A\rho m\tau/T$ (9)

To justify small overlap, α should be small. Due to reception at > 1 receiver, the chance of experiencing overlap at all receivers may be less than α^2.

For example, suppose $k = 2$, $\tau = 0.2\cdot10^{-9}$, m=4, $T = 100\cdot10^{-9}$, and $\alpha = 0.1$. From (9), we find

.

$d_A\rho = \alpha\, T/2mk\tau = 3.124$ senders in an antenna separation,

$R = 31.24/d_A$ megabits/sec./meter. Individual senders at 10 megabits/second.

As d_A is decreased, with k and α constant, the total delivery rate in bits/second/meter increases, and the transmitted energy/active user decreases due to shorter ranges. However, more antennas are required. The chance of transmission failure is roughly α^2, or 0.01 in this case.

B. Higher rates and the possibility of CSMA.

Let us look more closely at interference events in the one-dimensional network. Figure 7 shows a space-time diagram with 4 antennas and a number of possible senders starting at the labeled space-time positions. The vertical solid lines represent the four fixed antenna positions. The diagonal lines represent pulses traveling in time on transmission from a circled starting point. With one narrow pulse per transmission, the interference durations are very short. A sender is sending periodically during a packet transmission, so any information learned about the sending time can be used for decisions when to start a pulse train in the next period. Pulse trains rarely will begin in the same cycle. Let the desired signal emit a pulse at point X with coordinates (x,t) indicated by the dashed vertical and horizontal lines. Note that pulses originating at space-time points Z and W interfere with X's reception at an antenna to the right of X, but do not interfere individually with X at a left side antenna. A pulse from point R interferes with the X pulse on the nearest left side antenna of X, but not at the other antennas. Similarly, a pulse from point V interferes with the X pulse only at the immediate right side antenna.

As a general observation, a pulse from another source will interfere with the desired signal at all antenna reception points only if two transmitters are very close, such as within less than a meter from each other, and transmit their pulse at almost the same time. But if the two transmitters are so close, they could sense each other and avoid this kind of interference. (Usually one will send first, and the other would sense and select a different starting time.) However, two more distant senders, as pulses from V and R, could jointly interfere with X at its nearest antenna points. The chance that both would interfere in this way is roughly the square of the chance each individually would interfere. V and R would not interfere with X at X's second nearest antenna points, so X still might be received successfully there, though at a weaker level.

To eliminate the problem of interference with extremely close senders, assume that a sender will not send a pulse at a time close to where there is a received pulse with strength > S. This is related to the CSMA concept, except that weaker interferers are ignored, since they would be difficult to sense anyway [20, 21]. For simplicity assume a sender will pick a time at random, conditioned only on avoiding pulses with strength > S. For signals with strength < S, they are at a sufficient distance from X that they can't interfere on both sides of X. Figure 8 illustrates the critical regions and region avoided.

The avoidance region represents where a pulse would not have been initiated, else X would not have elected this starting time. It takes at least two interferers, one from each side, to interfere on both sides of a sender, excluding the very near senders, who are avoided. We would like to estimate the probability that X sends a transmission that is lost, given that n other packets are within range (that is, in either the same antenna interval as X or in an adjacent interval) are sending during at least part of its transmission. To simplify the problem, assume X is successful only if it is received without interference from this set at one of the two antennas at the boundary of its interval. This is pessimistic in that it ignores any chance that it may be received successfully at a next furthest antenna, or that it could be decoded successfully, possibly with the help of combining, despite one interference at each adjacent antenna. It is somewhat optimistic in that it ignores any interference at its adjacent antennas from signals outside the current and adjacent intervals. These other signals would be weaker, and in most cases would not interfere with decoding.

C. Approximate probability of no interference.

Assume the desired signal is in about the middle of the center region of the three regions depicted in Figures 7 and 8, that there are n other senders within the three regions, and each selects a pulse time uniformly over a span of T. Ignore the rare close sender, who will be avoided. Recall $p = m\tau/T$. The probability one of the n will not interfere at a particular antenna is about 1- p . It also has the same probability 1- p of interfering at the other antenna, but from the geometry it can't interfere with both the left and the right one. The probability none will interfere at a given antenna is about $(1-p)^n$, independent of whether the source is to the left or right.

To succeed, either none of the n must interfere on the (say) left antenna, or if i> 0 interfere at the left antenna, the remaining n-i must not interfere at the right antenna. Thus, the probability of success is

$$P(S) = (1-p)^n + \sum_{i=1}^{n} [\binom{n}{i} p^i (1-p)^{n-i}] \cdot (1-p)^{n-i} \qquad (10)$$

This reduces to

$$P(S) = (1-p)^n + (1-p+p^2)^n - (1-p)^{2n} \qquad \textbf{(11)}$$

With p = .02 and n = 8, P(S) ≈.98. Thus there is only about a 2% chance of being interfered with at both of the two nearest antennas. And it would be unusual to have as many of 8 interferers. Even with interference, there still is a high probability of successful decoding due to power differences, signal correlations, combining, and non collision at the two next nearest antennas.

D. Base-to-mobile communication.

The transmission in this section has been assumed mobile (auto) to base. Although this direction may not need to carry streaming high rate traffic, the ability to send bursts of information very fast is an asset. It allows many brief communications with very little time interference overlap. Also, the communication can be two-way using UWB. The base network can respond rapidly to requests and pass on communication through the stationary network, for continuous communication to a moving auto. The base stations can more conveniently coordinate their pulse trains to different mobile receivers. They would have more accurate location information about mobile senders based on receiving their packets. With access to an antenna on each side of the sender and successful deooding on one side, correlation with the two sides could discover the time difference of arrival of the signals from the mobile, and precisely locate its distance between the two sides. Knowing the exact location, it is easy to see when other interfering pulses are arriving at the mobile it wants to contact. See Figure 9.

VII. DISCUSSION AND CONCLUSIONS

Pulsed ALOHA and/or Wideband ALOHA have the following advantages:

1) Avoiding spreading codes except for a possible preamble, much higher data rates are easier to achieve.

2) Wide bandwidth and low energy constraints are a perfect fit for light traffic ALOHA. Energy constraints don't allow close to continuous transmission at the rates that such high bandwidths are capable of carrying, so high rate bursts experience low chance of collision.

. 3) Multiple antenna elements and multiple base stations can enhance total throughput and reduce needs for retransmission.

4) Equal received power for competing senders is not necessary. Unequal received power can actually be an advantage, as the significantly stronger of two colliding receptions can usually be decoded successfully. Power control can be exercised just to achieve energy efficiency, since other senders rarely overlap in time at all receiving points.

5) High data rates are easy to obtain and don't require different spreading codes to be assigned. The preamble can be the same pseudo-random pattern for all senders.

6) Handoffs can be avoided within a network of cooperating base stations.

7) In CDMA, it is difficult to use the principle of subtracting out a decoded stronger signal before decoding another signal because there are so many simultaneous signals. In pulsed ALOHA there usually is zero or one interfering signal, so subtraction is much simpler.

8) Although feedback is needed to acknowledge packets, the feedback signals can also carry power and traffic control instructions for a next sending. This can save in interference energy while also reducing energy drain in battery-powered systems. Also, the control instructions can provide stability, rate control, and can aid in collision avoidance.

9) A short message can be sent at a high data rate - many times faster than CDMA - thus reducing delay in sending the complete message.

10) Because data is sent as short periodic pulses, a potential sender could sense a nearby

transmission and time its sending to avoid collision

11) Higher power (within regulated limits) can be used for priority or to meet a deadline.

A multi-element antenna method has been suggested which has directivity-related features for UWB signals. It provides the receiver with multiple copies of a Pulsed ALOHA packet train, many of which do not collide with other senders. A two-dimensional array consisting of two linear strips orthogonal to each other is particularly effective. However, because of range restrictions currently imposed and multipath effects, the time differences between elements might not be enough to separate two pulse trains that collide at one element. The slight difference in time separations might be enough to use correlation to get better distinction between the interferers, but this could be somewhat complex to achieve.

Multiple base stations allow greater separation between receiving points, which can make the probability two simultaneous pulse trains will collide at two different receiving points almost independent. This isn't available with the wideband ALOHA method of sending the whole packet at once at the channel maximum rate, but wideband ALOHA can benefit greatly from the capture effect, which with fading gives randomly different captures at different receivers.

A simple one-dimensional model of antennas and base stations shows the possibility of sending at high rates from mobile senders between each antenna pair, with low energy per bit and infrequent packet loss. Usually such high rates are not needed from mobile to base, in which case the system becomes extremely simple and creates very little spectral energy use. The study considers only uplink transmission of data. Usually this is justified because the base-to-mobile communication is less of a collision problem. Possibly the base-to-mobile link could also use ultra-wideband signals; this possibility has not been investigated here.

REFERENCES

[1] N. Abramson, "Multiple access in wireless digital networks", *Proc. IEEE*, vol. 82, pp. 1360-1369, September 1994.

[2] J. J. Metzner. *Reliable Data Communications*, Academic Press, 1998.

[3] IEEE Journal on Selected Areas in Communications, *Special Issue on Ultra-Wideband Radio in Multiaccess Wireless Communications, December 2002.*

[4] L. Yang and G.B Giannakis,. "Ultra-wideband communications: an idea whose time has come," *IEEE Signal Processing Mag.*, vol. 21, pp. 26-54, Nov. 2004.

[5] A.F. Molisch, J.R Foerster, M. Pendergrass, "Channel models for ultrawideband personal area networks," *IEEE Wireless Commun. Mag.*, v. 10, pp. 14-21, Dec. 2003.

[6] W. C. Chung, N.J August, and D. S. Ha; "Signalling and multiple access techniques for ultra wideband 4G wireless communication systems, *IEEE Wireless Commun. Mag*, v. 12, April 2005, Page(s):46 - 55.

[7] M. Welborn, T Miller,. J. Lynch, and J. McCorkle, "Multi-user perspectives in UWB communications networks," *2002.IEEE Conf. on Ultra Wideband Systems and Technologies*, pp.271- 275.

[8] M. Z. Win and R. A. Scholtz, "Ultra-Wide Bandwidth Time-Hopping Spread-Spectrum Impulse Radio for Wireless Multiple-Access Communications," *IEEE Trans. Comm.*, V. 48 no. 48, pp. 679-691, April 2000.

[9] F. Ramirez-Mireles, "Performance of Ultra-Wideband SSMA using time hopping and M-ary PPM", *IEEE J. Sel. Areas in Comm*., vol.19, pp.1186-1196, June 2001.

[10] R.C. Qiu, H. Liu, and X. Shen, "Ultra-wideband for multiple access communications," *IEEE Commun. Mag.*, v. 43, pp. 80- 87, February 2005.

[11] N.J August,.Hyung-Jin Lee; and D.S. Ha, "An efficient multi-user UWB receiver for distributed medium access in Ad Hoc and sensor networks," *IEEE Radio and Wireless Conference*, pp. 455- 458. Sept 04.

[12] E. Baccarelli, M. Biagi, C. Pelizzoni, P. Bellotti, "A novel multi-antenna impulse radio UWB transceiver for broadband high-throughput 4G WLANs," *IEEE Commun. Letters*, vol. 8, pp.419- 421, July 2004.

[13] L. Piazzo, "Performance analysis and optimization for impulse radio and direct-sequence impulse radio in multiuser interference," *IEEE Trans. Commun*, v. 52, May 2004, pp. 801 - 810

[14] W Horie and Y. Sanada, "Novel CSMA scheme for DS-UWB ad-hoc network with variable spreading factor," *2004 Joint Conference on Ultra-Wideband Systems and Technologies*, May 2004, pp.361- 365.

[15] H.G. Schantz, "Introduction to ultra-wideband antennas," " *2003 IEEE Conference on Ultra Wideband Systems and Technologies*, pp. 1- 9.

[16] R.J.-M. Cramer,. R.A. Scholtz, M.Z. Win, "Evaluation of an ultra-wide-band propagation channel," *IEEE Trans. Antennas and Prop.*, v. 50, pp.561-570, May 2002.

[17] A. Hirata, T. Morimoto, Z. Kawasaki, "DOA estimation of ultra-wideband EM waves with MUSIC and interferometry," *IEEE Antennas and Wireless Prop. Letters*, v. 2, pp.190- 193, 2003.

[18] C. Bi and J.Y. Hui,."Multiple access capacity for ultra-wide band radio with multi-antenna receivers," *2002.IEEE Conf. Ultra Wideband Systems and Technologies* , pp. 151- 155.

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[19] T.G. Pratt and M.L. Wheeler, "Array processing in UWB localization," *2003 IEEE Conference on Ultra Wideband Systems and Technologies*, pp. 167-171.

[20] N. J. August, H-J. Lee and D. S. Ha, "Pulse sense: a method to detect a busy medium in pulse-based ultra wideband (UWB) networks," *2004 Joint Conference on Ultra-Wideband Systems and Technologies*, May 2004, pp. 366- 370.
[21] E.A. Homier and R.A Scholtz, "Rapid acquisition of ultra-wideband signals in the dense multipath channel," *2002.IEEE Conf. Ultra Wideband Systems and Technologies* , pp. 105- 109.
[22] K. Yu and I. Oppermann, "Performance of UWB position estimation based on time-of-arrival measurements," *2004 Joint Conf. on Ultra-Wideband Systems and Technologies*, May 2004, pp.400- 404.
[23] L. G. Roberts, "ALOHA packet system with and without slots and capture", *Comput. Comm. Rev.*, vol. 5, pp. 28-42, April 1975.
[24] J.J. Metzner, "On improving utilization efficiency in ALOHA networks", *IEEE Trans. Commun.*, vol. COM-24, pp. 447-448, April 1976. Reprinted in *Multiple Access Communications*, Edited by N. Abramson, pp. 298-299, IEEE Press, 1993.
[25] J.Arnbak and W. van Blitterswijk, "Capacity of slotted ALOHA in Rayleigh-fading channels", *IEEE J. Select. Areas Commun.*, vol. SAC-5, pp.261-269, Feb. 1987.
[26] C.C. Lee, "Random signal levels for channel access in packet broadcast networks", *IEEE J. Select. Areas Commun*, vol. SAC-5, pp. 1026-1034, July 1987.
[27] I.M.I. Habbab, M. Kavehrad, and C.E. Sundberg, "ALOHA with capture over slow and fast fading Radio channels with coding and diversity", *IEEE J. Select. Areas Commun*, vol. SAC-7, pp.79-88, Jan. 1989.
[28] C.T. Lau and C. Leung, "Capture Models for Mobile Packet Data Networks", *IEEE Trans. Commun.*, vol. 40, pp. 917-925, May 1992.
[29] A. Bottcher and M. Dippold, "The capture effect in multiaccess communications-The Rayleigh and landmobile satellite channels", *IEEE Trans. Commun.*, vol. 41, pp.1364-1372, Sept. 1993.
[30] M. Zorzi, andR.R. Rao, "Capture and retransmission control in mobile radio, *IEEE J. Select. Areas Commun.*, vol. 12, pp. 1289- 1298, Oct. 1994.
[31] F. Borgonovo, M. Zorzi, L. Fratta, V. Trecordi, and G. Bianchi, "Capture-division packet access for wireless personal communications, " *IEEE J. Select. Areas Commun.*, vol. 14, pp. 609-622, May 1996.
[32] M. Sidi and I. Cidon, "A multi-station packet radio network", *Performance Evaluation 8*, pp. 65-72, North-Holland 1988.
[33] K. Sakakibara, "Performance approximation of a multi-base station slotted ALOHA for wireless LAN's", *IEEE Trans. Vehicular Tech.*, vol. 41, pp. 448-454, Nov. 1992.
[34] J. J. Metzner, "On the benefits of fading in a multi-base packet radio network," *Proc. 1994 Princeton Conf. on Iinformation Systems and Sciences,* pp. 456-461, Mar. 1994.
[35] S. Zhou, M. Zhao, X. Xu, J. Wang, and Y. Yao, "Distributed wireless communication system: A New Architecture for Future Public Wireless Access", *IEEE Commun. Mag.*, pp. 108-113, Mar. 2003.

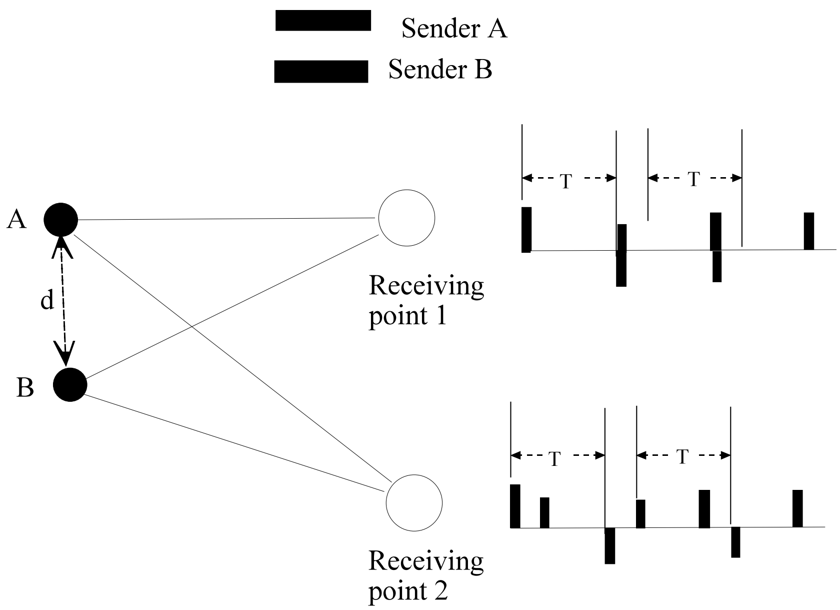


Figure 1. A and B collide at point 1 but not at point 2, due to time differences.

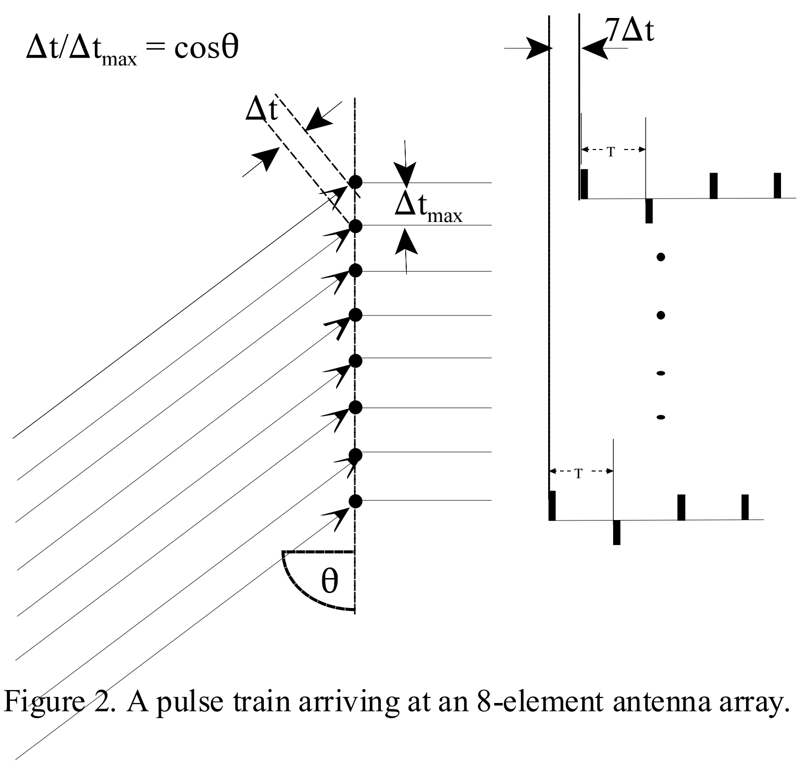
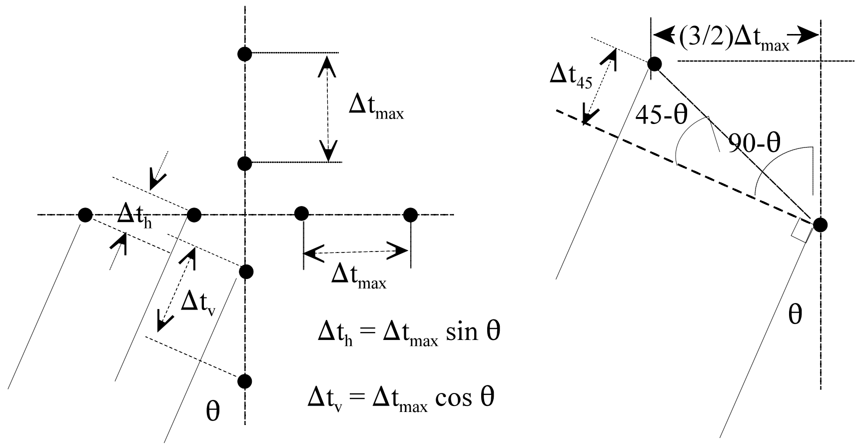


Figure 2. A pulse train arriving at an 8-element antenna array.



a. Computation of Δt_h and $\Delta t_h v$ b. left and bottom arrival difference.

Figure 3. A two-dimensional array.

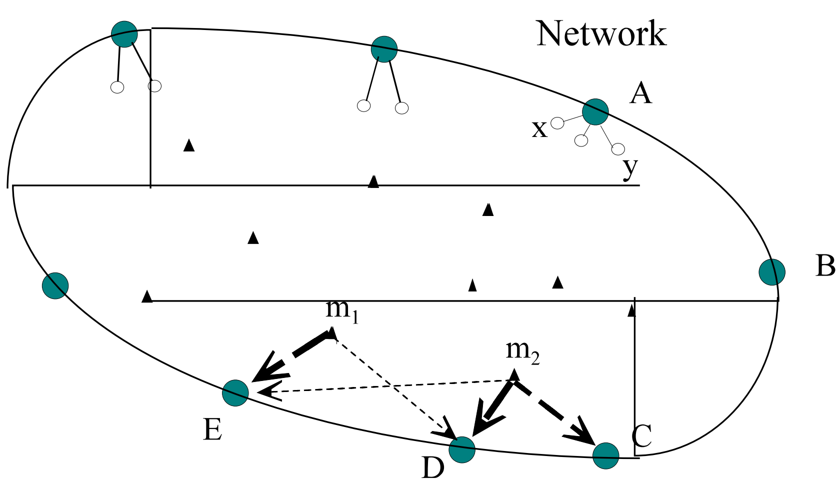


Figure 4. The Multibase network.

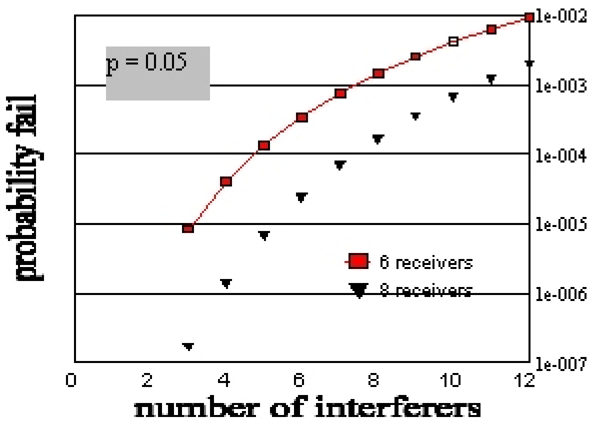


Figure 5. Probability that a sender finds all multi-base receptions interfered with.

```
         j      k       l        m       n        o        p        q        r        s        t        u
----------x------x-------x----|---x-------x--------x---|---x--------x-------x---|--- x-------x------- x
                A             |           B            |           C            |           D
```

Figure 6. A one-dimensional network of antennas and base stations.

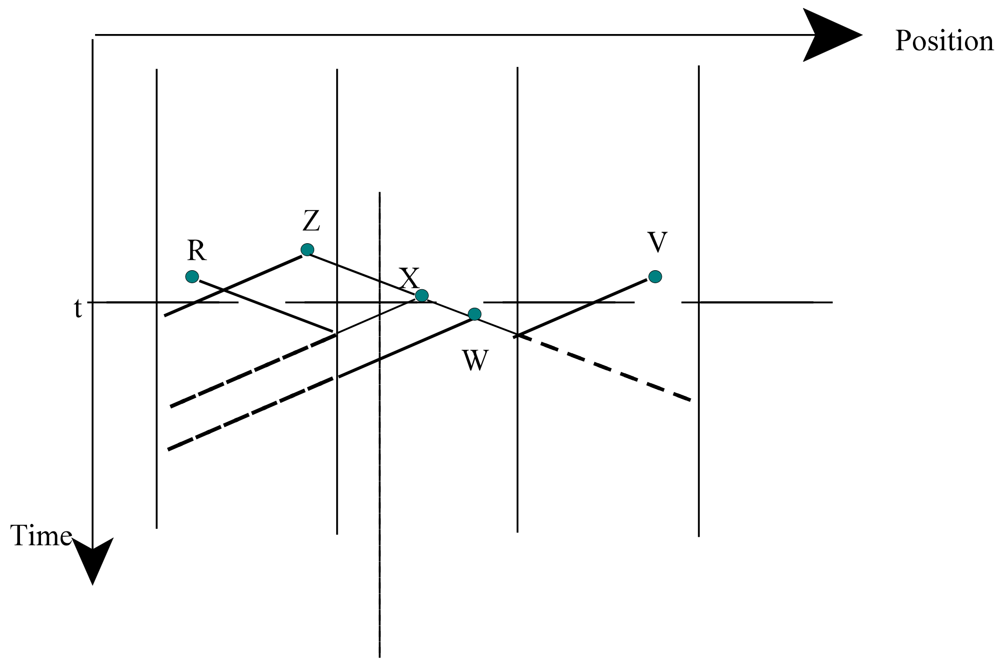


Figure 7. Collision events at four adjacent antennas.

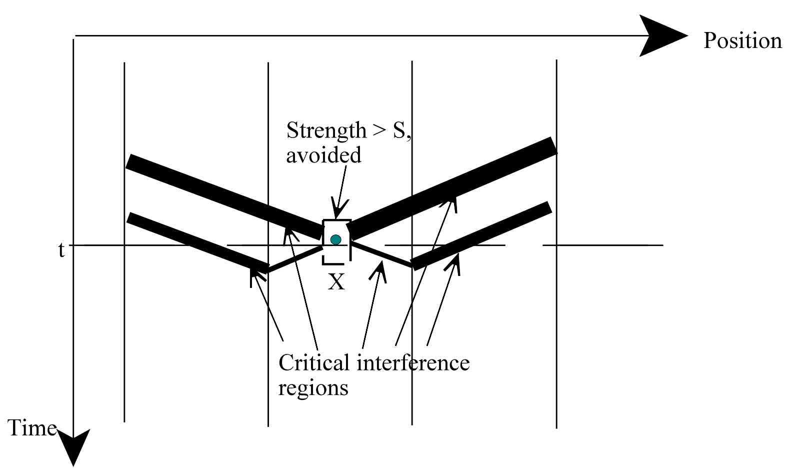


Figure 8. Regions where collisions can occur and regions which would be avoided.

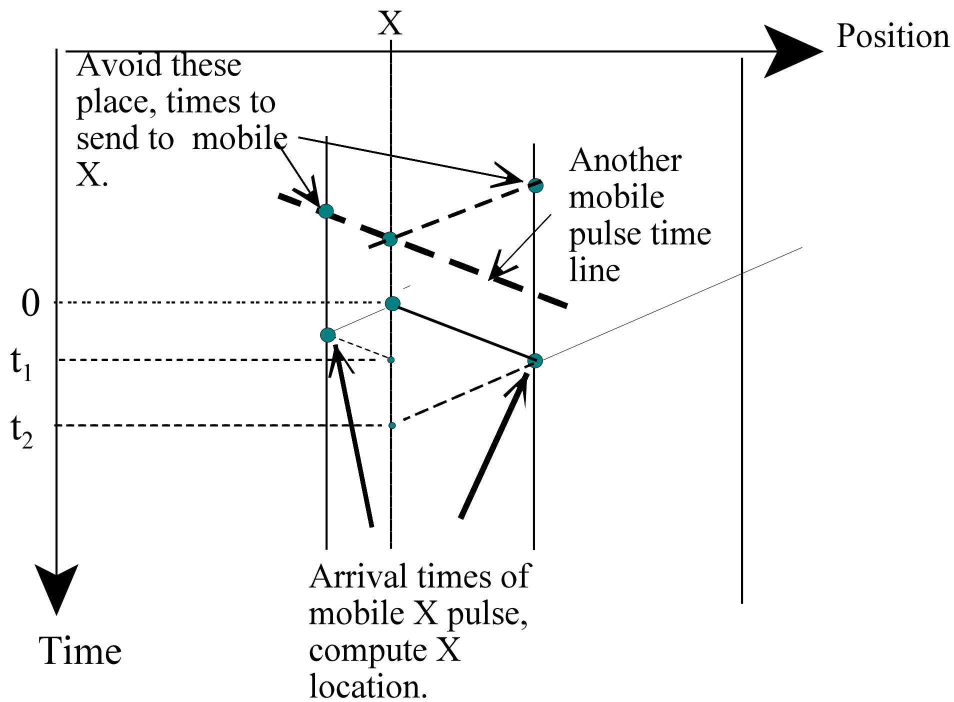


Figure 9. Space-time lines for computing X location and choosing a pulse response to avoid interference.