Dynamic Radio Location under Extreme Multipath Conditions

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Abstract:

Dynamic Radio Location (DRL) uses propagating radio waves to estimate point to point distance and relative angle—sufficient information to calculate a position vector [*x y z*]. In unobstructed environments free of RF reflectors and diffractors, positioning is reliable, continuous, and computationally light. However, highly cluttered channels speckled with ray reflectors and diffractors, generate multiple paths (multipath) forming homogenous composites of phase shifted and amplitude modified rays. We investigate this problem from a brief theoretical approach, enhanced with graphical illustrations to develop an insightful view of the challenges, and analyze current solutions and limitations. Finally, we assert that a new solution is available due to a recent communications development that performs well in multi-path environments-MIMO radio architectures, utilizing Alamounti's space-time coding. In addition, micro technology advancements have provided us with highly accurate, yet low power and small inertial measuring accelerometers—MEMs technology. These technologies are limited on their own, and require significant computational power to integrate them together—a task uniquely satisfied via the powerful Virtex-5 FPGA.

I. Introduction:

Dependable real-time streaming positioning of nodal (team member) movements and locations has been an illusive goal for military, police and fire-fighting organizations. Knowing relative positions and motions of a group of soldiers entering a hostile building, provides a tactical advantage while reducing risks of friendly fire, and enabling rapid adaptability to dynamic situations. A small handheld PDA indicating individuals' positions is illustrated in figure 1, and would be an applicable example. The dotted lines represent path movements and a color-specific dot is a specific node (team member). To the right of the handheld unit is a magnified view of streaming information that is shared among all the nodes. The information indicates if an active LOS radio location is present, or time since a last active position coordinate was recorded. Additional location information is streamed via inertial sensors via a MIMO communication link, when the line-of-sight (LOS) link fails. The balance of this paper discusses (II) Basic enabling technologies for relative positioning. Also, a simple expansion from basic radio positioning, to advanced positioning, is illustrated graphically; (III) technological limitations, and (IV) new solutions from recent advancements.

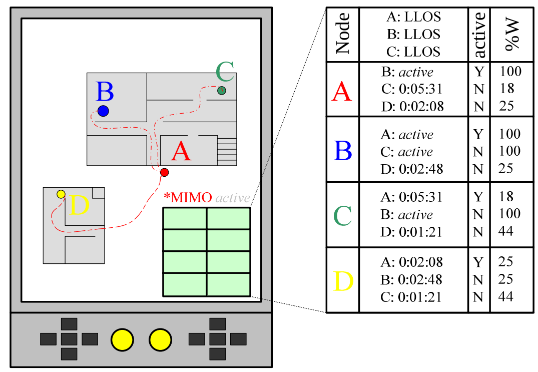


Fig. 1: (L)PDA view of several 'node' positions and paths. (R) Expanded reading indicates active positioning, or time of inertial sensor dependence.

II. Enabling Technologies:

Single antenna positioning radios estimate relative distance to a target, but not position. Relative distance is the scalar distance or the radius 'r' of a circle, as seen if figure 2. Multiple antenna systems can further estimate location by cross-correlating each antennas' received signal to predict a 2-dimensional picture of distance 'r' and angle 'theta', as depicted in figure 3.

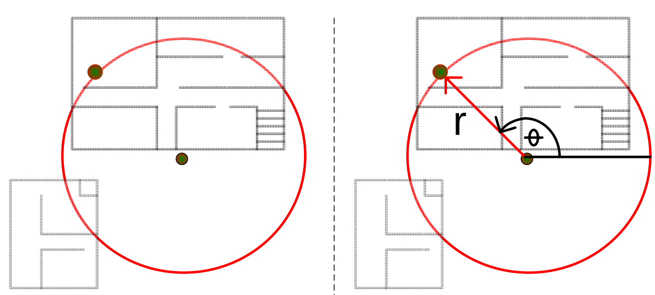


Fig. 2a: (L) Radial distance resolved with single antenna.
Fig. 2b: (R) Multi-antenna system resolves radius and angle.

The illustrative descriptions of figures 2a and 2b can be expanded to multiple users in 'cooperative networks', where information is shared between all nodes, using time division multiplexing (TDM) or frequency division multiplexing

(FDM) to provide orthogonality in estimating user positions. Orthogonality removes the potential ambiguity due to interfering signals by assigning predefined time intervals or unique center frequencies from which each node pings a location message, represented by figure 3.

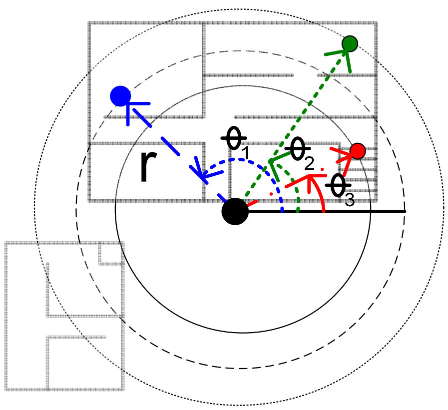


Fig. 3: Multiple Users are uniquely identified due to time and/or frequency orthogonality.

Communications systems usually suffer distortions due to reflections and diffractions of in-band signals; however, the power of the offending reflected waves is either substantially lower than the main signal or the reflection is adaptively canceled by the signal processing equalizer to mitigate the undesired reflections and pass only the main signal path. In some situation, a direct path may not exist, but a large reflected signal may arrive, indistinguishable from a direct LOS path, resulting in a miscalculation of both angle and distance—location, as seen in figure 4.

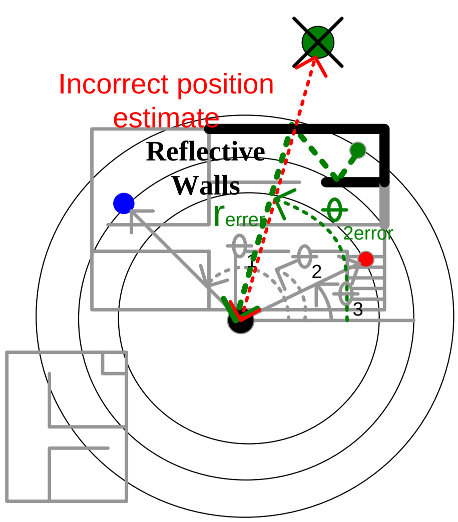


Fig. 4: Incorrect estimate of angle and position due to strong reflection of the signal.

Figure 4 depicts a common situation where a direct path is much smaller than the reflected path, resulting in an incorrect estimate of path length and angle. Also, figure 4 indicates where the angle might incorrectly estimate the nodal position by illustrating the incorrect distant ‘r’, designated by the red dashed line and ‘false’ node marked with an X.

Radio positioning has been successful through multiple wall-boundaries of an office buildings using very wide bandwidths, or ultra wideband architecture. A successful demonstration is plotted in figure 5, where the blue points, or line indicate the path traveled by a beacon, superimposed on the actual office building floor plan.

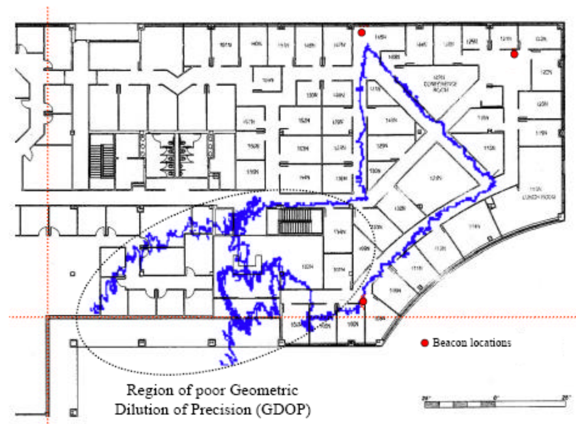


Fig. 5: UWB positioning data-trail as node navigates the hallways of a building, Multispectral, Inc. [5]

III. Technology Hurdles:

The distorted angle and distance calculations caused by the reflections indicated in figure 4 limit the range and reliability of positioning technologies. If the reflected path is strong enough to dominate the direct LOS path, which is common for reinforced concrete and steel buildings, this error may be undetectable.

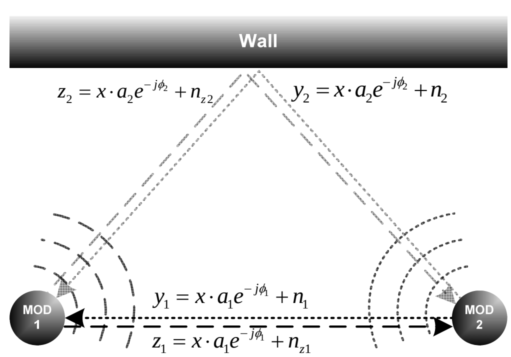
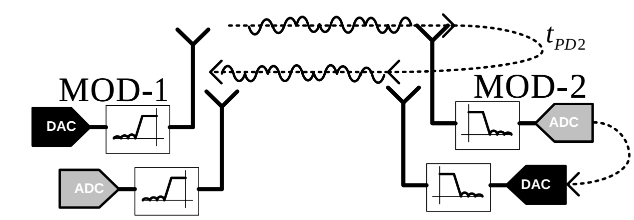


Fig. 6: Multipath signals received and transmitted from two nodes, or users.

The problem is further complicated when numerous signal rays phase align such that the information content of the signal is distorted beyond recovery. The two problems of multipath signals are positioning is compromised and communication is degraded. The equations seen in figure 6 can destructively interfere if the multipath component, bouncing off the wall is a multiple wavelength offset, plus 180 degrees. If the multipath is severe, which is common, communication fails, as does the ability to dynamically track individual positions. This has now rendered the individuals without communication and unsure of team positions.

A simple view of how an ultra wideband positioning measurement is performed is illustrated in figure 7. A chip-code is transmitted from modem one (MOD-1), received and retransmitted, unprocessed, by MOD-2 and finally received by MOD-1. With hardware and software propagation times for both radios known a priori, a correlation spike indicates the time of flight, and the resulting radius is calculated by subtracting the propagation times.



$t_{PD1} = t_{aADC} + t_{DRx} + t_{DTx} + t_{aDAC}$ $\quad$ $t_{PD2} = t_{aADC} + t_{DRx} + t_{DTx} + t_{aDAC}$

Fig. 7: Two modem TX / Rx system, with propagation times which are removed from the time-of-flight calculation.

IV. Technological Solutions:

i. Ultra wideband communications: has the ability to track a user through walls and discontinuous partitions. However, UWB fails when the material is excessively reflective or absorptive, i.e. steel and reinforced concrete. Figure 5 shows the results of a UWB tracking system created by Multispectral Solutions, Inc. (www.multispectral.com), where positioning is successful through numerous gypsum walls and wood beams.

ii. Advanced signal processing: If a cooperative network (team) has a known start position or reliable relative position estimate, advanced signal processing can provide dependable position estimates in the presence of limited multipath reflections. The solution requires continuous analysis and cognitive processing of billions of calculations per second. This requirement is easily accommodated in newly released, lower power FPGAs [3]. A small insight into where advanced cognitive processing will provide a reliable solution is examined be reviewing figure five. Advanced processing identifies the discontinuity created when the user's direct path fades and the reflected path becomes dominate, which is the sequence illustrated in figure 8.

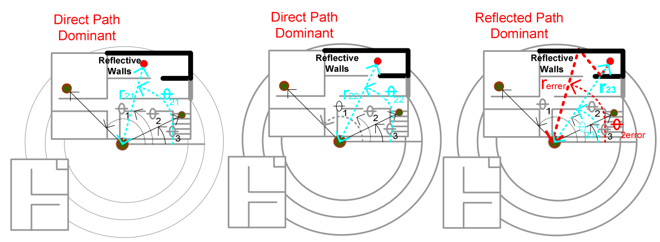


Fig 8. Target moves to the right until direct ray path is lost and reflect path appears dominant.

By continually tracking the dynamic node, signal processing filters detect the discontinuity caused when the node goes behind the reflective wall of figure five. Figure 9 illustrates the 'swap' in dominance and the discontinuity seen in the prediction of the magnitude distance 'r'.

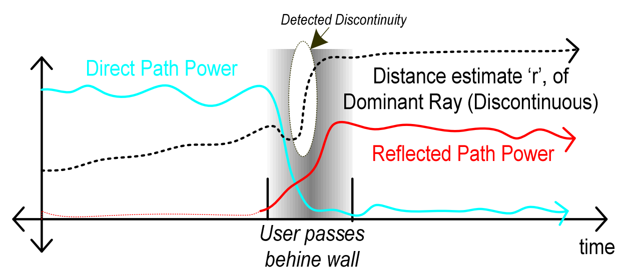


Fig 9. Power levels over time as user moves behind reflective wall and reflective path becomes dominant path.

Subsequent to detection of the discontinuity, an adaptive equalizer 'tags' the reflected path and cancel it, while continually tracking the much smaller yet detectable direct path; thereby, correctly estimating position even in the presence of much larger reflections.

This process of recognizing new discontinuities can be broadened to remove numerous paths until the dynamic range of the hardware is violated; fortunately, with a limited amount of total transmit power from the tracked node, each new reflection divides total power into more paths, reducing peak magnitudes and thereby reducing the risk of dynamic range saturation. A second problem arises when several discontinuities occur simultaneously (multiple reflected rays appear simultaneously); however, this is still manageable given sufficient processing power.

iii. Advanced signal processing with MEMs and MIMO: MIMO architecture using Alamounti's "Simple Transmit Diversity" algorithm [2] is uniquely positioned to solve multipath communications problems herein mentioned. As the tracked radio signal node suffers more multi-path distortion as reflective interferers increase, the MIMO link becomes stronger. As a matter of fact, MIMO performs poorly in direct LOS or dominant path channels. MIMO's 'signal quality' actually increases with each additional multi-path interferer.

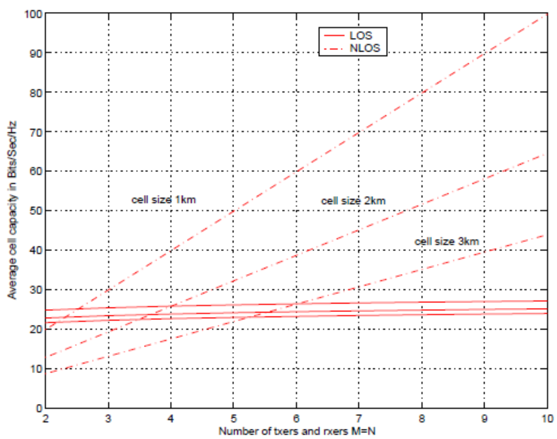


Fig. 10: Cell capacity for high-rate systems at radii 1, 2, 3 km (top to bottom). Line of sight (LOS) solid lines, and non-LOS dashed. X-axis is number if antennas, Tx = Rx.

We maintain continuous data-communication via MIMO; however, MIMO doesn't contribute to range finding and positioning (at least not directly). The key is that the communication link never fails and data streams freely to all team members in the nodal network. MIMO doeen't perform the chip 're-transmit' depicted in figure's 6 and 7. MIMO overcomes the multi-path induced failures allowing straming communication of the accelerometer readings to the rest of the team members. Figure 11 indicates Mod-2 streaming back accelerometer reading, but Mod-1 receives two copies of the signal, which may suffer from destructive interference.

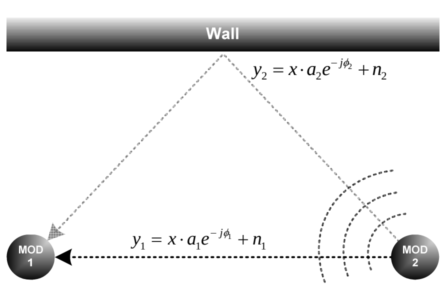


Fig. 11: Mod-1 receives a multi-path 'space-time coded' signal, which is corrected via space-time decoding.

Micro-MEMS accelerometer technology provides 3-degree of freedom (triple-axis) acceleration vector [x y z]. Analog Devices MEMs accelerometers [4], via double integration (Figure 12) and appropriate coordinate transformations provide precise positioning relative to the last reliable radio locating position (x, y, z)'. These devices are continually reset when accurate radio location chip-codes are received, thus reducing or removing drift errors.

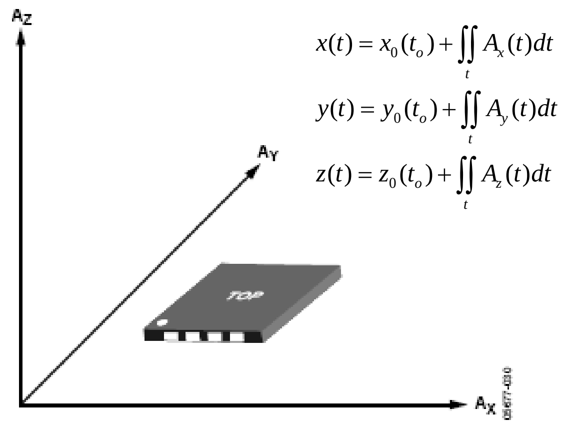


Fig. 12: Tripe Axis accelerometer and related equations to update position vectors via double integration of acceleration vector.

With the MIMO communication link continually active, updates from the doubly integrated acceleration vectors are continually streamed among the nodal users (or begin streaming when the radio-positioning estimates fail). MEMs accelerometers suffer from 'drift' which is the tendency to accumulate 'biased-noise' causing small accelerations reading even when stationary. Fortunately, drift errors can be gain-scheduled into a reliability-algorithm determining calculating position estimates. Over short intervals of a few minutes, the accelerometers can be trusted. When a reliable radio-positioning ping is received (i.e. the user has a reasonably good channel estimate due to movement), the accelerometer drift can be 'reset' and according to the ray traced position estimate. Furthermore, the cognitive radio is learning the reliability of the accelerometer each time it is updated and compared with the streaming accelerometer reports.

As the nodal-positioning network inter-communicates, the probability of another node having a more reliable position estimate of a third node increases. That 'third party' estimate can be deemed the most reliable and relayed to all the users as the most probable position of third-node, as illustrated in figure 13.

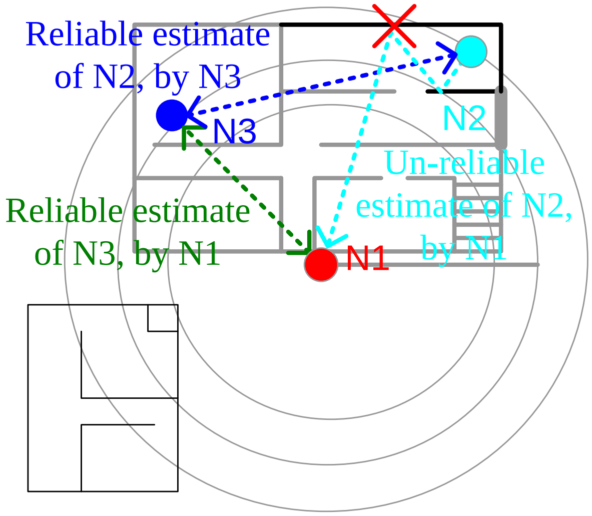


Fig. 13: Position estimate hand-offs in cooperative positioning network.

Conclusion: Advanced signal processing technology combined with MEMs' positioning capability and MIMO communications' robust dependability in multipath environments, results in the first reliable solution to cooperative network radio positioning. These dawning technologies put Cubic in a prime position to take the lead in Cooperative Network Positioning: Alamouti's MIMO scheme has just recently become realizable in the FPGA, MEMs accelerometers, smaller than a dime, have only been available for a couple years, and signal processing demands surpassing the 10-50 billion operation per second threshold are now satisfied in Xilinx Virtex 4/5-FPGAs (similar ops/sec would have required a super-computer 10 years ago, now we can put that power in a hand-held PDA).

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