LOCALIZATION AND BEAM ALIGNMENT

Methods for Efficient Alignment of Transmission and Reception Beams

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Executive Summary

Billions of user devices are expected to crowd into 5G-Advanced and especially 6G networks in the near future. Due to the exponentially increasing demand for real-time high-volume throughput, it is essential that future communications be carried on narrow "beams" focused on the intended recipient. Beams enhance the signal level at the recipient, while saving transmission power and minimizing interference at other receivers. At the receive end, the recipient can optimize the received signal by aiming a "reception" beam toward the transmitter. Transmission and reception beams greatly reduce background noise, and save power by focusing the transmitted energy where it is needed. Energy conservation is an increasing priority for base stations, and especially for battery-constrained user devices, mobile users, and IoT devices.

Directional beams must be properly aligned. Current procedures for beam alignment involve extensive scanning and feedback messaging - a significant consumption of time and energy, hardly suitable for the fast-cadence communication demanded of next-generation wireless. What networks need are new procedures designed to enable base stations and user devices to efficiently align their transmission and reception beams with each other, in real-time, at negligible cost.

Examples detailed below [1] show how a base station can align all the user devices at one time, by transmitting a special alignment pulse in which the signal varies by angle, all around the base station. Each user device measures the as-received signal, and thereby determines its direction relative to the base station. The user device then informs the base station of its angle. Both uplink and downlink beams are instantly aligned - without scanning. As a further simplification, the base station can list its own latitude and longitude in the system information messages that are continually broadcast, enabling a prospective user to aim its beam toward the base station right from the start. Mobile user devices, with continually changing alignment conditions, can inform the base station of their planned trajectory upon entry, so that the base station can track them as they move along roadways and other predictable trajectories. For further convenience, base stations can map out the "dead zones" in their area, boosting power temporarily when someone enters each problem region. For ultimate efficiency, AI-based algorithms can assist base stations in localization, beam optimization, and power control.

By these means and others detailed below, base stations and user devices can align their beams for optimal communication reliability, with minimal consumption of resource area, minimal transmission energy, and negligible wasted time. Such improvements will be critical to network performance, and hence to user acceptance, in the high-density, high-throughput networking demanded by next-generation market applications.

Alignment Pulse with Angle-Dependent Phase

Networks are seeking a simpler, more efficient way to align the base station beams with individual user devices, and for the user devices to align their beams with the base station. A new and very efficient way to accomplish mutual beam alignment is a special "phased alignment" pulse, transmitted by the base station with an angle-dependent phase. The phased alignment pulse can be transmitted around the base station, with a phase that varies from 0 to 360 degrees according to the direction. Each user device can determine its direction by measuring the phase of the received signal. For accuracy, a calibrator pulse, with a uniform phase in all directions, may be transmitted before or after the alignment pulse, and the user devices can compare the two received signal phases, thereby determining the angle while canceling many errors. The user device then reports the received phase, or the corresponding angle, to the base station for mutual beam alignment.

Figure 1 shows a phased alignment pulse schematically. The star is the base station and the diamond is the user device. The bold arrows represent electromagnetic transmission, overlapping beamlets in eight directions as indicated by the angles A=0, A=45, etc. Each beamlet, with a phase P=0, P=45, etc. blends with the adjacent beamlets, providing a linear phase-angle response. The base station can also transmit a calibration pulse, with the same phase in all directions, for comparison. Thus the user device, sitting at an angle of 70 degrees, would measure a net phase of 70 degrees at its location. The user device can then transmit a beamed acknowledgement toward the base station, informing the base station of the received phase or the corresponding angle. The user device and the base station beams are thereby aligned for optimal communication.

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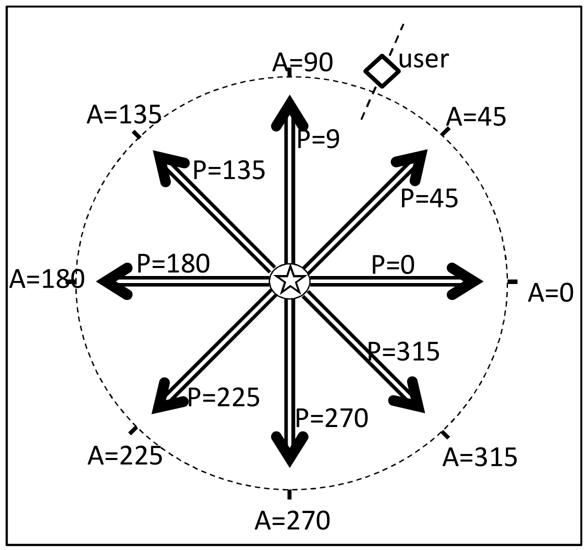

Fig. 1 Phased alignment pulse transmission.

Figure 2 shows how an antenna cluster can generate the phased alignment pulse. A single antenna would have a difficult time trying to emit the full 360-degree phase distribution spatially, but with multiple panels, it is straightforward. Each panel is designed to generate narrow beams with a pre-programmed phase in a particular direction. For the phased alignment pulse, each panel may be programmed to generate three beamlets in three directions. (This is done by adding the beam production instructions for three overlapping beamlets as shown, each beamlet aimed in a different direction and with a different phase.) A user device receives the blended overlap signal at its location, a weighted average of the beamlet phases, thereby obtaining a phase which is linearly related to the angle.

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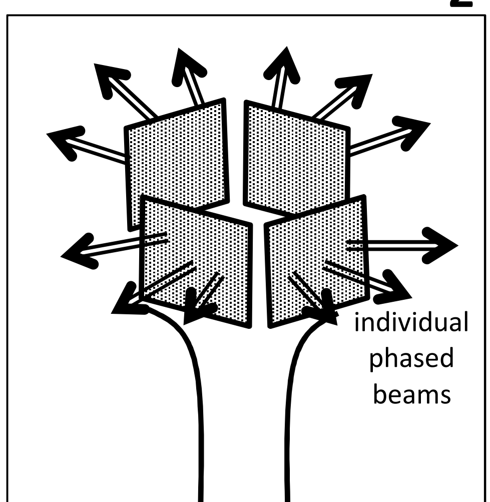

Fig. 2 Beamlets emitted around 360°.

Figure 3 shows how a phased alignment pulse can be constructed from individual beamlets, partially overlapping. A single beamlet is shown in bold. When combined with neighboring beamlets at different angles and phases (8 shown at 45 degree intervals), the blended resultant can closely approximate a linear phase-vs-angle distribution. The user device can measure the phase of the received signal, generally a weighted combination of two blended beamlets, and thereby determine its angle from the net phase received. All of the user devices of the network can be aligned using a single phased alignment pulse, and one calibration pulse. This represents a huge reduction in transmission energy, resource consumption, and time relative to the old beam-scanning technique.

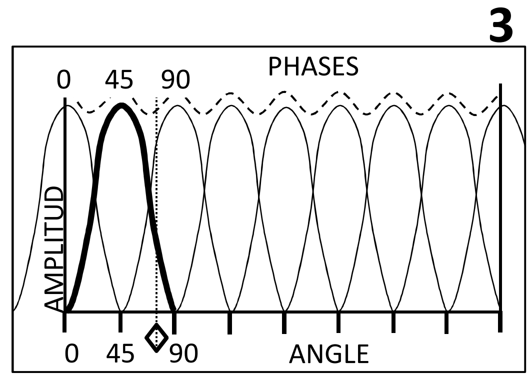

Fig. 3 Each beamlet has different phase.

Figure 4 shows the linear phase vs angle for the beamlets of Fig. 3. With proper adjustment of the shape and spacing of the individual beamlets, the resultant distribution at the user devices can be a linear function of the angle around the base station as shown. In this case, the phase is detected by a user device, sitting at an angle, as viewed by the base station, of 70 degrees relative to North. The user compares the received phase to the calibration phase, and thereby determines its angle from the base station. The user device can then aim its own transmission and reception beams toward the base station at the detected angle plus 180 degrees.

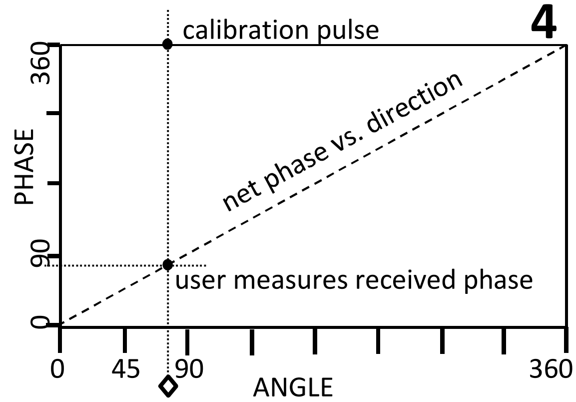

Fig. 4 User measures phase at own location.

Figure 5 shows how the user device can obtain even higher angular resolution with a "vernier" pulse. In this example, the base station emits two alignment pulses, plus the calibration pulse. The first pulse is like Fig. 4, a 360-degree phase change in 360 degrees of angle. The second alignment pulse is a "vernier" pulse, with much higher phase progression, in this case 360 degrees of phase in just 90 degrees of angle. All of the user devices in the network can thereby measure their location angle by comparing the received phases of the calibration pulse and the two alignment pulses. Users determine their location angle unambiguously, with high precision, from just three transmitted signals, without scanning.

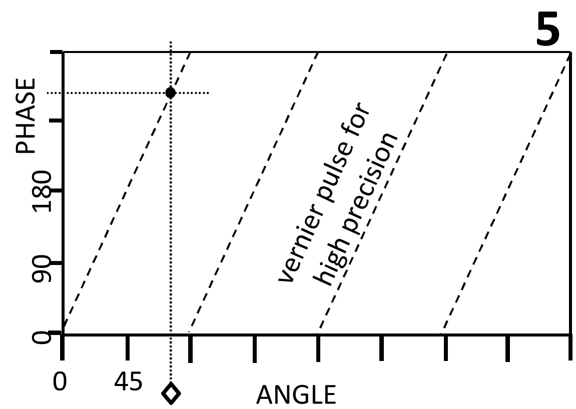

Fig. 5 Vernier pulse has multiple cycles.

Many low-cost wireless devices, such as IoT sensors, have isotropic antennas which are unable to form directional beams at all. Nevertheless, all wireless devices can detect phase quite effectively, and therefore can compare the calibration and alignment pulse phases. Each device can then report the angle or phase difference back to the base station as described, so the base station can use its directional beams in communications with those devices thereafter. Thus even the most basic IoT devices can benefit from the phased alignment beam procedure, by providing location information to the base station.

Alignment Pulse with Angle-Dependent Amplitude

The previous example shows how the base station can align beams to all of its user devices with a phased alignment pulse in which the phase varies with angle. In the following method, the alignment pulse has an angle-dependent amplitude instead of phase.

Figure 6A shows the spatial distribution of an alignment pulse that has amplitude varying with angle, in one quadrant. The base station can transmit an alignment pulse with a high amplitude at some angles and a low amplitude at other angles. The user device can measure the amplitude at its location, and determine its angular direction relative to the base station. For disambiguation, the base station can transmit several such pulses, each rotated by various angles.

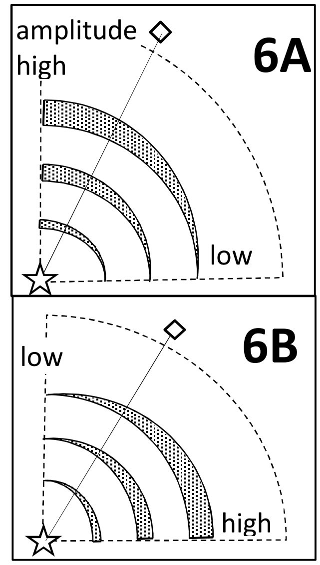

Fig. 6A-B Amplitude varies with angle.

Figure 6B shows a second pulse with a reversed distribution of amplitude versus angle. The user compares the two amplitudes at its location, and thereby determines its angle relative to the base station. Again, multiple transmissions at different angles may be useful, such as at 0 and 90 degrees orientation. Also, the "low" amplitude does not need to be zero. For measurement accuracy, the amplitude could vary from, say, 0.3 to 1.0 times a maximum value. The receiver is expected to know the format.

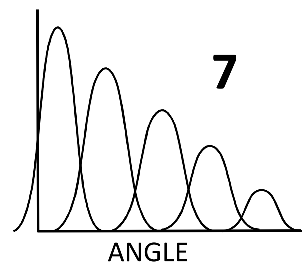

Fig. 7 Amplitude beamlets.

Figure 7 shows how the transmitter can generate a linear amplitude ramp by transmitting a set of simultaneous overlapping beamlets with different amplitudes, aimed in different directions in one quadrant. The user device measures the received amplitude at its location, which is the weighted sum of the beamlet amplitudes, weighted by how much of each beamlet appears in the user device's antenna.

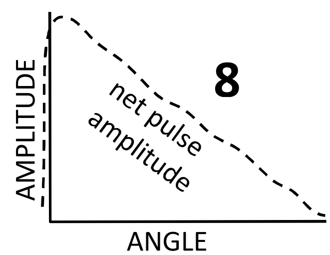

Fig. 8 Linear distribution.

Figure 8 shows the resulting smooth linear distribution of amplitude versus angle in 90 degrees. The base station can transmit a single alignment pulse in which the amplitude varies linearly with the angle, between the low and high values, in a predetermined pattern. User device can calculate its angle from the data, or it can transmit the data to the base station and let the base station calculate the angle. Either way, both the base station and the user device become instantly aligned.

Figure 9 shows how a user device (diamond) can determine its angle relative to the base station by measuring the received amplitude in two alignment pulses and a calibration pulse. One alignment pulse (short dash) has an amplitude varying from max to min to max, in 360 degrees. The other alignment pulse (long-dash lines) is a vernier pulse that varies from max to min to max every 90 degrees. The calibration pulse (solid line), has the same amplitude in all directions. The user device measures the three received amplitudes (black dots) to determine its angle precisely.

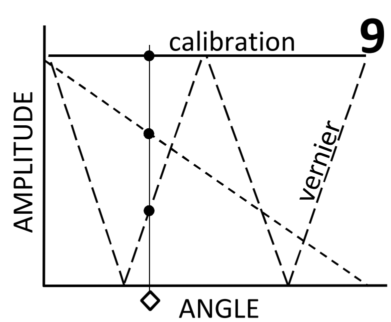

Fig. 9 High resolution vernier.

Base Station Displays Its Location

Mobile user devices often struggle to find an appropriate base station and to initially log on. It would be helpful if the base stations indicated their geographical location as early as possible in the initial access procedure, so that user devices could then communicate using directional beams for the remainder of the registration, and thereafter.

Figure 10 shows the first signal that a prospective user device detects from a base station, the SSB (synchronization signal block) message that base stations periodically transmit. The PSS and SSS assist with initial synchronization, and the PBCH blocks provide various system information for subsequent reception. The two empty areas beside the first symbol are unused.

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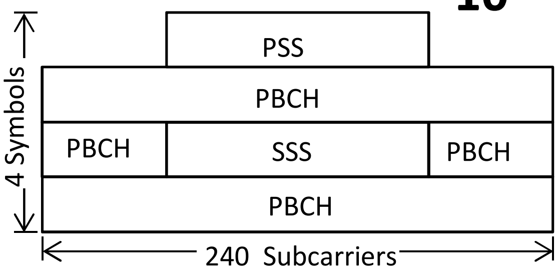

Figure 11 shows a modified SSB including the latitude and longitude of the base station, encoded in the unused portions of the first symbol. Since the receiver is not yet synchronized with the base station, two short-form QPSK demodulation references DM are also provided, so the receiver can determine the phase by comparison and thereby demodulate the LAT-LON data. The receiver can then calculate the direction toward the base station from its current position, thereby enabling the user to aim its reception and transmission beams at the base station.

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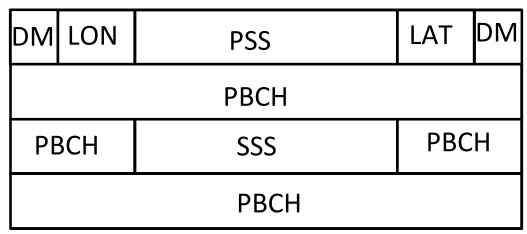

Figure 9C shows an alternative version of the modified SSB, adapted to accommodate reduced-capability receivers with lower bandwidth capability, as well as others that have difficulty interpreting the coordinates in the first symbol, despite the demodulation references. In this version, the latitude and longitude information is placed in the last symbol-time, long after the receiver has synchronized with the base station. Short-form demodulation references are also provided for convenience. Another "optional" PBCH symbol may be added if additional space is needed for specifying all the network data. Thus the total message size is 5 or 6 symbol-times.

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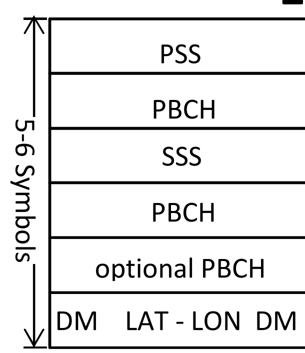


After determining the location of the base station from the latitude and longitude provided in the SSB, the user device can calculate the angular direction toward the base station relative to geographical North. Then, using an electronic compass or other means to determine the direction of geographical North, the user device can configure its antenna to generate a narrow transmission beam and a narrow reception beam centered on the base station. The user device can then inform the base station of the angle. Preferably the user device informs the base station of its angle as early as possible in the initial access process. For example, the user device can append its location information or angle information onto the initial RACH random access message, or one of the other access messages, or a separate message after registration. Beaming during the initial access procedure enhances the signal levels received by both the user device and the base station during the registration procedure, and in all future communications.

Reception Beam Alignment

Users may need special help from the base station to align their reception beams toward the base station. This is due to limitations in the user device (such as a reduced-capability IoT device). The base station can assist those user devices by transmitting a set of uniform test signals, all at the same power level, same frequency, and same phase. The uniform test signals may be transmitted time-spanning, that is, occupying successive symbol-times at a specific subcarrier frequency, at a predetermined time which the user device knows about. The user device can then attempt to receive those test signals while varying its reception beam across some range, and thereby determine which reception angle provides the best reception. Assuming reciprocity, the user device can then use that same angle for uplink messages.

Figure 13 shows a base station transmitting a series of uniform test signals (solid arcs) in successive symbol-times, at a pre-arranged time, while a user device cell phone varies its reception beam (dashed) in various directions. The user device thereby determines the direction of best reception, and likewise the best transmission, to the base station for future communications. If the mobile user device subsequently turns, it can use an electronic compass to compensate the beam direction, without having to do a beam scan, saving both time and power.

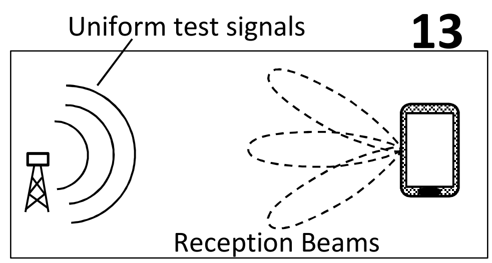
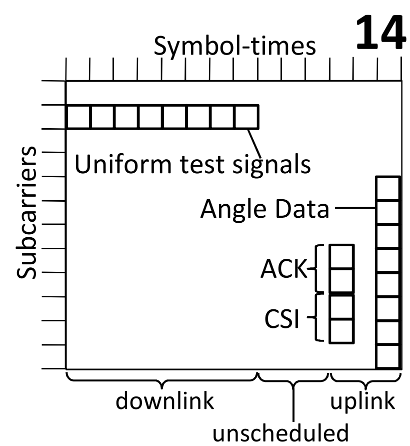


Fig. 13: User adjusts its reception beam.

Figure 14 shows a portion of a resource grid, with symbol-times across the top and subcarriers vertically, representing one resource block of one slot at some numerology. In the downlink scheduled portion, the base station transmits uniform test signals consisting of time-spanning, identically-modulated message elements to assist all the user devices of the network in aligning their reception antennas simultaneously. Each user device determines the angle of optimal reception and transmits an acknowledgement to the base station using that angle. In one case, the user device also transmits a signal quality feedback CSI as well. In another case, the user device transmits a reply message to the base station indicating its optimal reception angle, so that the base station can transmit future messages to that user at the same angle.



The base station can include the uniform test signals in a system information message, such as appended to the SSB message which they receive first. The user device can align its reception beam at that time, by varying its reception direction during the uniform test signals. The user device finds the angle of optimal reception before seeking the other system information messages. As a further option, the uniform test signals may precede the SSB, thereby enabling the user device to receive the SSB with greater clarity. There is no need for the receiver to be synchronized with the base station for determining which of the uniform test signals has the highest amplitude because the test signals are not modulated.

In some cases, the base station can transmit the uniform test signals to a particular user device individually, in a directed beam, instead of broadcast. In that case, the user device would provide the acknowledgement and possibly the CSI after aligning its reception beam, but would include the updated angle message only if the user device had changed location since the last alignment.

Beam Alignment for Mobile Users

Maintaining beam alignment is at least as important for mobile user devices as for stationary users. However, mobile users have at least five problems that stationary users do not: (a) the alignment angle changes as the mobile user moves, (b) the directionality changes when the mobile user turns, (c) the Doppler frequency corrections change as the mobile user moves relative the base station, (d) the power requirements change as the distance to the base station changes, and (e) the power requirements also change when the mobile user passes behind an obstruction. The same issues arise when the user is communicating in sidelink to another user.

Figure 15A shows how a mobile user (vehicle) can align its beam with the base station if it knows the location of the base station and geographical North. The user device then informs the base station of the angle. Alternatively, the user informs the base station of the user's location and planned trajectory, so the base station can track the user over time while employing directional downlink beams.

Figure 15B shows how the mobile user device and the base station must both adjust their beams as the user moves, to keep each other in alignment. The adjustment depends not only on the user device's lateral motion, but also on its radial distance from the base station.

Figure 15C shows how the mobile user readjusts its beams when it turns a corner. The mobile user device must continually adjust its beam direction to compensate for its changing direction as well as location.

The mobile user can help the base station maintain beam alignment by telling the base station the current location, speed, and direction of travel at the first communication. The user device can then update the information whenever it turns or changes speed.

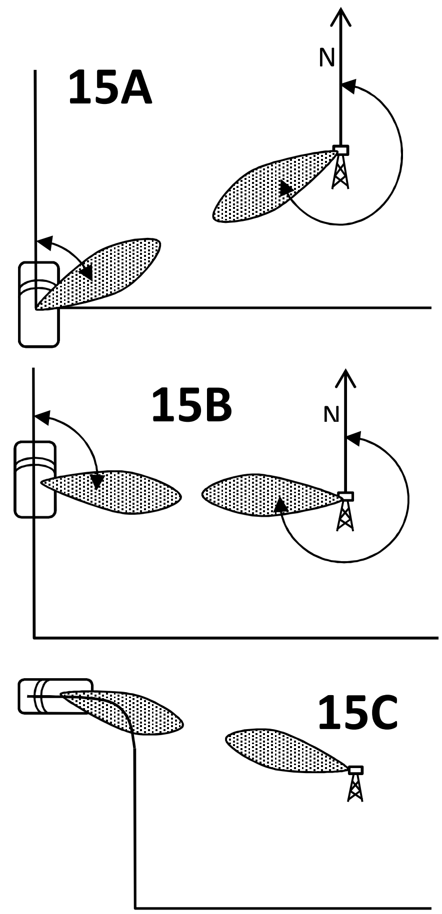


Fig. 15A-B-C: Mobile user keeps beam aimed at base station as it travels.

In addition, the base station can keep a map of the area, including roads for vehicles, sidewalks and trails for pedestrians, and so forth. The base station can locate the user's initial position on the map, setting the directional beams and beam power accordingly. The base station can then revise its directional beams and beam power based on the user's planned speed along each road or path, keeping the user in focus without wasting power and resources on unnecessary beam scans. The base station may also account for stop signs and other expected speed and direction changes. For example, the base station can determine, from the user's initial coordinates, which road the user starts on, and then extrapolate the user's time-dependent location along the road as it curves on the map, and thereby keep its beam directed at the mobile user without the need for frequent beam scanning. The user device can update its speed and direction if they change significantly. In a crowded network region with limited available bandwidth, both the mobile user device and the base station can save time and power by calculating the optimal beam directions based on location data, and by updating the locations according to a planned trajectory of the mobile user. They can resort to an old-fashioned beam scan only if required by an unexpected change in the user's motion or other beam-loss event.

Power Boost for Obstructed Locations

Everyone is familiar with "dead zones" where reception is poor. To maintain the required communications reliability, the base station can compensate by mapping the dead zones in its area ahead of time, measuring the attenuation at each location, and then providing extra transmission power whenever a user device passes through one of those regions.

Figure 16A shows a dead zone situation in which a car passes behind a hill. The base station has previously determined that there is a dead zone in that region, and how much attenuation it represents. If the base station knows that the mobile user is on the road that passes through the dead zone, and if the base station knows when the mobile user is scheduled to enter and exit the dead zone, then the base station can apply the extra transmission power for reliable communication. This should be transparent to the user.

Figure 16B shows a map of the area, in which the base station has measured the attenuation or receptivity at numerous positions along roadways, and possibly other places where pedestrian users go. In this example, the vehicles have informed the base station of their initial locations, speeds, and directions, after which the base station calculates their positions along roadways. When one of them turned onto a side street, it informed the base station of the turn. The base station knows that the street passes through the dead zone, and can then calculate when the user is likely to enter and exit the dead zone based on the user's speed. The base station can thus apply the predetermined additional transmission power to downlink messages for that user during the obstructed interval. The base station is also prepared for a weaker uplink signal, and may take steps to compensate its reception as well while the user is in the dead zone.

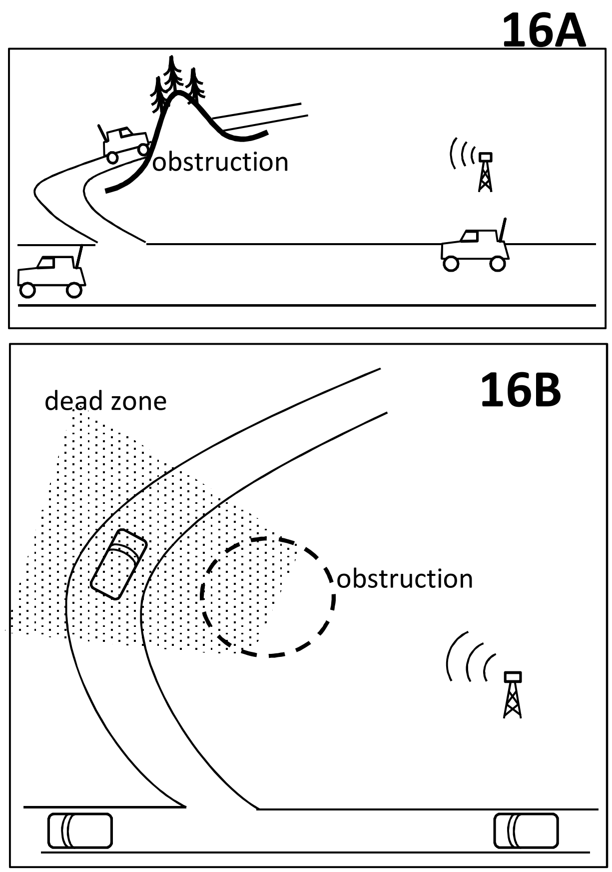


Fig. 16 A-B: A mobile user device in a dead zone. Base station increases power to compensate.

In this way, the base station, in cooperation with each mobile user device, can virtually eliminate dead zones. No costly beam scanning is needed at any time. Substantially improved network reliability can be provided, at virtually zero cost after the receptivity map has been prepared.

AI Applied to Localization and Alignment

Artificial intelligence can greatly assist in several aspects of beam optimization, including alignment, power, and localization. Figure 17, for example, shows how a neural net AI model can be trained to recommend the best transmission power level for each downlink message individually, based on three categories of input information (network factors, the message itself including distance to recipient, and the electromagnetic environment). In determining the optimal power setting, a host of complex and competing interests must be balanced, such as avoiding further background noise, yet providing enough transmission power to likely avoid a costly retransmission, while remaining sensitive to the other networks within radio range since they could be adversely affected as well.

The AI model inputs are shown as squares, linked to internal functions or "nodes" (circles) in several layers (only 2 shown), which are finally accumulated as the output prediction (triangle). For training, a "ground truth" is provided, based on an expert network operator's judgement or on the subsequent results of each particular transmission. The AI prediction is compared to the ground truth, and if they differ, certain adjustable parameters in each of the internal functions are incrementally adjusted to bring the prediction more in agreement. When good performance is demonstrated under a wide variety of network, message, and environmental factors, the model is ready for deployment in base stations.

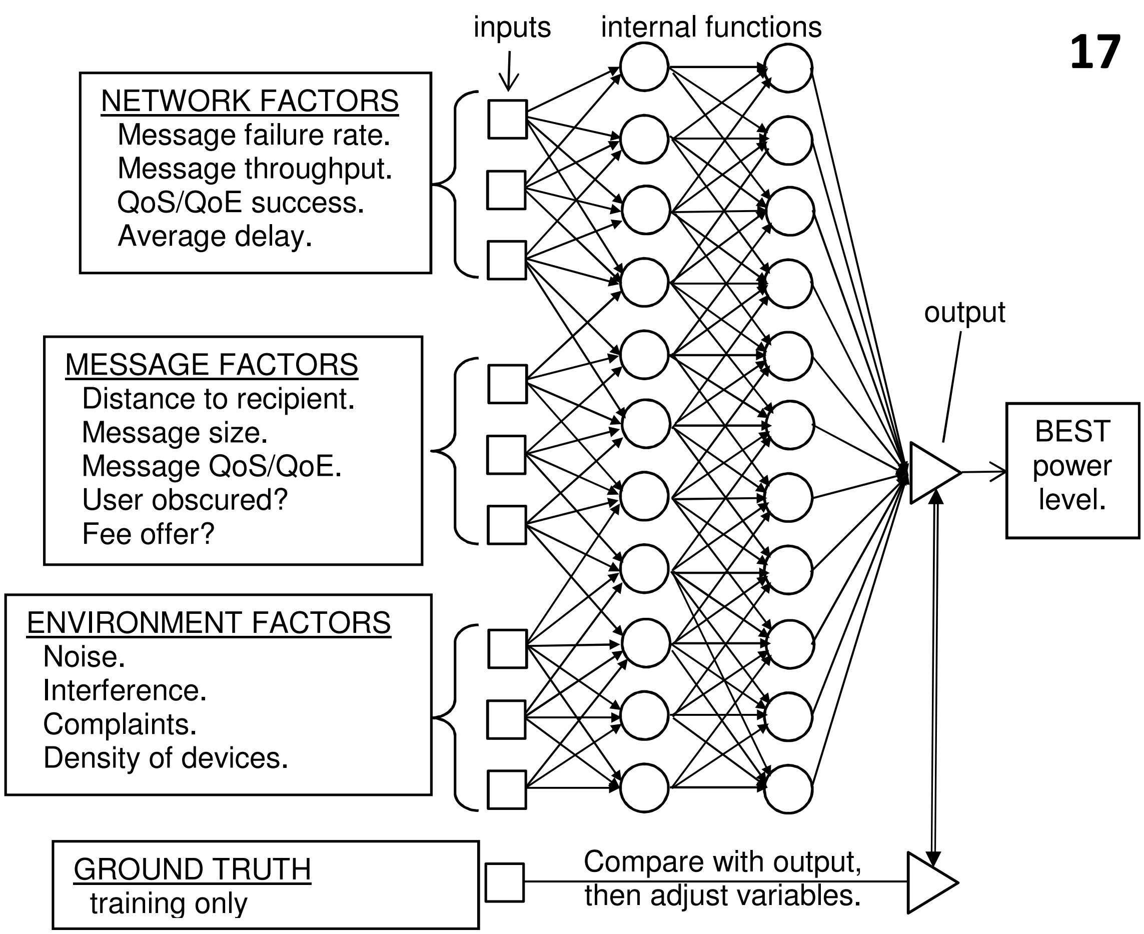


Fig. 17: An AI model exploits hidden correlations between the input parameters, and calculates a most-likely prediction indicated by those correlations.

Figure 18 shows how a single node of the AI model works. Each internal function or node is a simple, self-contained calculator with adjustable variables. It takes in values from the model inputs or from the previous layer, and combines them algebraically using an offset-weighted sum as shown (only 3 inputs shown, usually many more). The X values are the function inputs, the O values are variable offset values, and the W values are variable weighting factors. That sum is then limited ("squashed") to the range of ±1, using a sigmoidal limiter function. The squashed results are then distributed to the next layer or to the final output of the model.

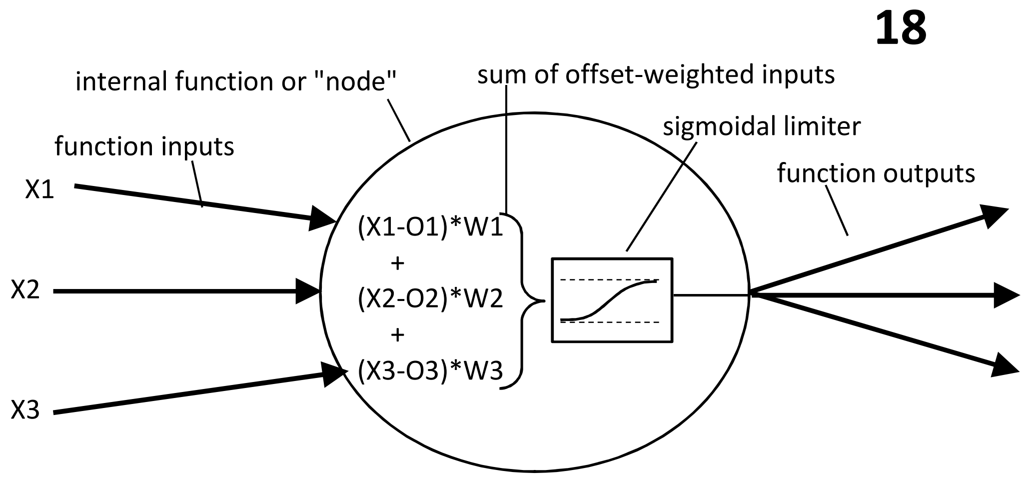


Fig. 18: Internal workings of an AI node.

Although the operation of one node is rather simple algebraically, when combined with many other nodes and many input factors, the AI model can often uncover subtle correlations that enable surprisingly good predictions. Sometimes the correlations are so complex, no human could ever understand them - but the computer easily uses them for predictions (easily, that is, after being trained on millions of examples).

Large AI models have billions of inputs, billions of layers, and billions of adjustable variables, and they rely on massive machine learning (as opposed to human intervention) to adjust those variables. After millions or billions of examples, such models can provide amazingly good predictions in whatever field is covered by the examples. For example, in network operations, AI can help improve the throughput, fault rate, latency, and energy consumption - all at negligible cost after training.

Regarding the deeper functionality of AI, the figure clearly shows that each node is just a simple calculator, and hence the AI model is basically a large multi-channel calculator. Despite the "artificial intelligence" name, it is not intelligent in any meaningful sense of the word. It is a computer algorithm or a gate array designed to detect correlations in the example data, and nothing more. Although AI models can become very good at finding intricate correlations, and then using them to make surprisingly accurate predictions, it has no "will" or agenda. Like any other inanimate tool, it can be used for good or evil, depending on how it is implemented by a human operator. If it does evil, blame the human operator, not the computer.

Conclusion

Narrowly focused beams are the future of wireless communications. Keeping those beams pointed in the right directions will require improved methods for alignment and localization. The methods disclosed herein provide efficient and economical new procedures for beam alignment and angular localization. With a few pulses of tailored, angle-dependent transmission, the base station can provide alignment service to all the users in a network simultaneously. By tracking each mobile user within a prepared reception map, the base station can continually maintain each communication link and virtually eliminate dead zones. With advanced AI-based control, the network can manage beam alignment, transmission power, and resource allocation for optimal user satisfaction and economy, all while minimizing energy consumption.

Networks implementing these techniques can keep ahead of demand, especially in the crowded communication spaces anticipated in the coming years, and thereby avoid the problems experienced in previous generations of wireless. We encourage standards organization such as 3GPP to include these beam alignment and localization procedures in future releases, so that developers can provide the advantages of rapid, low-cost beamformed communication to all users.

Glossary

3GPP (Third Generation Partnership Project) is the primary wireless standards organization.
AI (Artificial Intelligence) is a computer-based calculation emphasizing correlations in input data.
IoT (Internet of Things) refers to wirelessly-connected, autonomous, sensors and actuators.
QPSK (Quad Phase-Shift Keying) is a two-bit phase-only modulation system with 4 phase states.
RACH (Random Access CHannel) represents one step of user access to a network.
SSB (Synchronization Signal Block) is a system information message broadcast by base stations.
SIB1 (System Information Block type 1) is another system information message.
A "node" is an internal function of an AI model containing adjustable variables.
A "short-form demodulation reference" is a short transmission indicating certain modulation levels.
A "phased alignment pulse" is a transmission that varies in phase with angle.
An "amplitude alignment pulse" is a transmission that varies in amplitude with angle.
"Angle data" is an indication of an angle toward a particular transmitter, relative to North.
"Reciprocity" means that the same angle optimizes both transmission and reception.
"Uniform test signals" are identical signals during which a receiver can align its reception beams.

References
[1] Patents on beam alignment and localization can be found at www.UltraLogic6G.com.

US Patent/Publication	Title
11,398,850	Rapid Doppler Correction for Mobile V2X Communication in 5G/6G
11,411,612	Location-Based Beamforming for Rapid 5G and 6G Directional Messaging
11,424,787	AI-Based Power Allocation for Efficient 5G/6G Communications
11,438,033	Location-Based Power for High Reliability and Low Latency in 5G/6G
11,509,381	Resource-Efficient Beam Selection in 5G and 6G
11,533,084	Automatic Adjustment of Transmission Power for 5G/6G Messaging
11,581,919	Transmission Power Compensation by Attenuation Mapping in 5G and 6G
11,611,375	Location-Based System Information and Doppler Correction in 5G/6G
11,644,522	Triangular Beam Configurations for Rapid Beam Alignment in 5G and 6G
11,652,533	Rapid Alignment of User Directional Beams in 5G/6G Networks
11,689,249	Geographical Localization of 5G/6G Network Users and Base Stations
11,782,119	Phased Beam-Alignment Pulse for Rapid Localization in 5G and 6G
2023/0100826	Throughput Enhancement by Location-Based Power Adjustment in 5G and 6G
2023/0179261	Automatic Condition-Based Adjustment of Transmission Power in 5G and 6G
2023/0246699	Low-Complexity Procedure for 5G/6G Beam Alignment
2023/0283322	Beamforming Communication Method for Wireless Devices in 5G and 6G
2023/0408622	Low-Complexity Beam Alignment by Directional Phase in 5G and 6G
2024/0045013	Deterministic Low-Complexity Beam Alignment for 5G and 6G Users