In-network Angle Approximation for Supporting Adaptive Beamforming

Hiba Mallouhi
ELTE Eötvös Loránd University
Budapest, Hungary
hibamallouhi@inf.elte.hu

Jaspreet Kaur
University of Glasgow
Glasgow, United Kingdom
j.kaur.1@research.gla.ac.uk

Hasan Tahir Abbas
University of Glasgow
Glasgow, United Kingdom
hasan.abbas@glasgow.ac.uk

Sándor Laki
ELTE Eötvös Loránd University
Budapest, Hungary
lakis@inf.elte.hu

ABSTRACT

There is a great interest in utilizing P4 for in-network computing along with programmable data planes. This use is emerging as a new network paradigm that can not just reduce the complexity but the delay as well. Beamforming is now an integral feature of modern wireless communication systems and its implementation calls for an accurate beam alignment by estimating the direction of signal arrival. However, this estimation is computationally complex, especially in a dynamic environment where a user is constantly on the move. In this paper, we propose a user-assisted in-network method to optimally approximate the angle of arrival by segmenting the cell area into an exponentially binned grid and make use of the advantages offered by programmable data planes and their match-action table (MAT) logic. The method expects location messages periodically reported by user equipment, processes them in the network and reconfigures the base station antennas accordingly, implementing user-assisted in-network beam control. The proposed method is implemented in P4 and runs on a Tofino ASIC. Our evaluation proves a theoretical bound on the absolute error of the proposed MAT-based angle approximation and shows that it is in accordance with the empirical error distributions. Moreover, there is no significant increase in errors attributed to the latency of various control cycle times (less than 100ms) and the user's movement at moderate speeds (of less than 90km/h.) We also show that the resource usage is only affected by the size of the TCAM table used to store the angle approximation values and that the proposed method has no significant per-stage resource usage on the pipeline.

CCS CONCEPTS

• **Networks** → **Programmable networks**; **In-network processing**; **Mobile networks**.

KEYWORDS

5G, P4, In-Network Computing, Beamforming

ACM Reference Format:
Hiba Mallouhi, Jaspreet Kaur, Hasan Tahir Abbas, and Sándor Laki. 2022. In-network Angle Approximation for Supporting Adaptive Beamforming. In *P4 Workshop in Europe (EuroP4 '22), December 9, 2022, Roma, Italy*. ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3565475.3569076

1 INTRODUCTION

The electromagnetic spectrum available to current-day consumers in a wireless network is increasingly getting stretched owing to the massive demands of data. Exploring higher frequency in wireless communication networks is one of the telecommunications sector's most crucial tasks in order to address this problem [13]. As a result, millimetre wave (mmWave) frequencies, which range from 30-300 GHz, are being investigated for use in the fifth generation of wireless communication networks (5G). One of the most promising technologies for future wireless networks, mmWave can accommodate high data rate transfers thanks to its abundant spectrum resources [7, 10, 13–15]. High propagation loss, which results in short propagation lengths, and signal blockage brought on not only by building materials and greenery but also by the human body and high oxygen absorption are some of the difficulties that mmWave must overcome [8].

Beamforming [5], which has many advantages, such as increased coverage at a cell's edge, enhanced signal quality, tracking the user equipment (UE), and enabling collaboration among base stations (BS), is one practical solution to mitigate the reduced propagation distance in mmWave communications. The high route loss that mmWave signals experience can be partially offset by directional beamforming, but it creates a challenging beam alignment problem. In order to establish the beamforming direction, a BS particularly needs to know the direction of arrival (DOA) of its users. Searching exhaustively for all potential matches to get the optimal beam alignment is a natural way to carry out beamforming training to increase alignment accuracy [12]. However, this technique consumes so much computational power. As a result, we propose to realize a P4-enabled switch that can perform (or approximate) basic mathematical operations and also hold the prior information in form of tables. This is done to estimate the angle from the transmitter

---

EuroP4 '22, December 9, 2022, Roma, Italy

ACM ISBN 978-1-4503-9935-7/22/12…$15.00
https://doi.org/10.1145/3565475.3569076

to the mobile user or vice versa by means of performing simple trigonometric calculations.

The motivation behind this study is as follows:

1. Complex tasks can be performed at the network switch level (data link layer.)
2. A truly distributed architecture.
3. P4 is going to reduce the congestion caused at the network layer by moving some of the operations and tasks to the link layer.
4. Network customization as a result of software-defined radio. As a result, we get flexibility; ideal for 5G networks.

Beamforming requires training of the network that determines the best beams within a wireless channel. There are various algorithms such as binary search beam training over a beamforming code-book. Typically this pre-configuration is done at the MAC sub-layer (part of the link layer.) MAC protocols provide control to physical devices such as antennas, etc. Although the state of the art in beamforming undoubtedly increases the network performance at the user end, work needs to be done to assess the overall increase in performance when the backhaul network is also considered.

In this paper, we propose a user-assisted in-network approach for accurately steering the beam towards the UE. Accordingly, we assume that the UE periodically reports its location to an in-network computing node (i.e., a P4 switch in the transport network or RAN) that uses its location and the base station information to compute the angle that is then used to reconfigure the beam between the base station and the UE. We also show that the complex task of angle computation can be approximated with match-action tables (MATs) in the data plane and the approximation errors can be bounded. The accuracy of the proposed system is examined in more dynamic scenarios with a moving UE and different control latency, while the resource usage of our Tofino-based implementation is also analyzed. We believe that P4 and P4-enabled devices can help to develop unique edge-cloud or fog network architectures, and enable the provision of network services through which a user can avail personalized services [2–4, 6].

2 SYSTEM DESIGN

Figure 1 depicts the segmented network scenario that is taken into consideration in this paper. Mobile users are attached to 5G network and indirectly connected to switches in the access aggregation network by means of core network protocols. We assume that some of the switches in this network are P4-programmable. The mobile user periodically sends its GPS location to a P4-switch, the P4-switch computes the angle of user equipment (UE) around the corresponding base station and send a configuration message to the base station to direct beam to the UE. We believe that this user-assisted in-network method can reduce the control latency and increase the steering of beam much smoother and faster than traditional approaches.

2.1 Angle Approximation in the Data Plane

Figure 2 summarizes the key conceptual steps of our in-network method for beam angle computation. Figure 2a shows the positions of two UEs inside the range of a base station and the desired Angles of Arrival (α_1, α_2) that needs to be determined and used to steer the two beams. The absolute coordinates of UEs are first transformed to a relative coordinate system where the origin (0,0) represents the base station's location. We assume that the shape of the cell is similar in the four quadrant around the base station and thus we use the absolute value of the two coordinates to determine the base-angle. One can observe that the base angle of a UE with relative location (a,b) can be computed as $\beta = \arctan |b|/|a|$ (resulting in an angle in the first quadrant). However, computation of the arctangent function is not supported by P4 and in general far too complex for a P4-programmable switch.

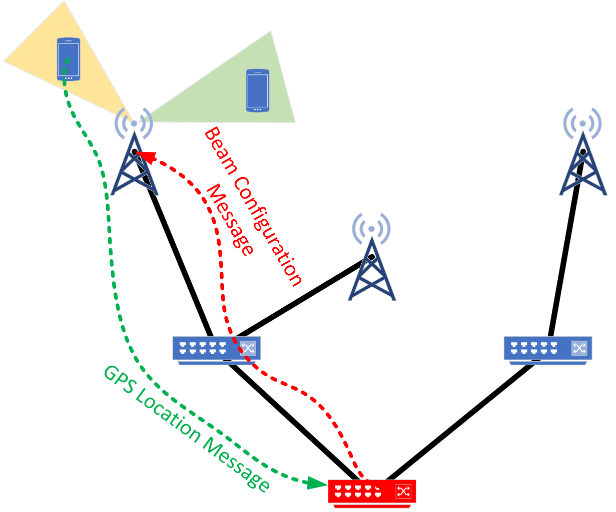
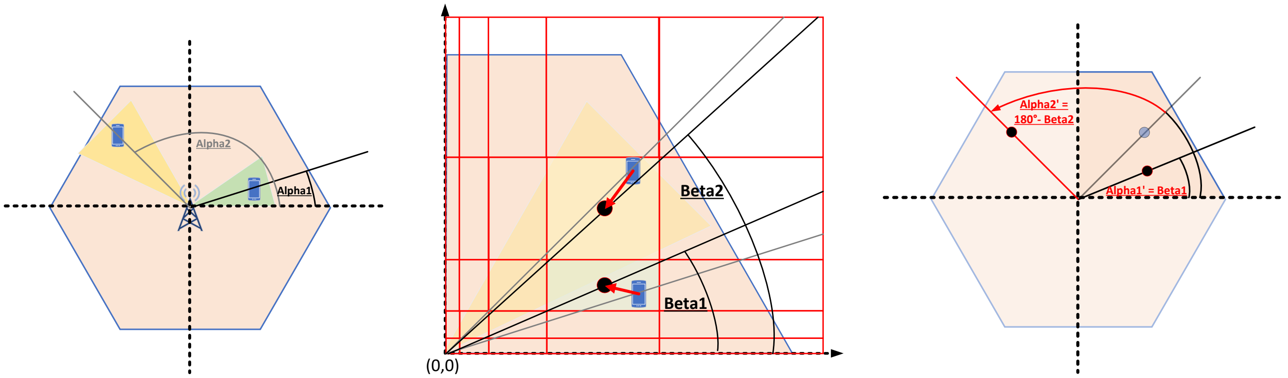


Figure 1: Main concept of the proposed user-assisted in-network beam-control.

Our approximation method is shown in Figure 2b. We take a grid with exponential binning and approximate the UE's location with the centroid of the containing grid-cell. These centroid points are then used to determine the approximated base-angles (β_1 and β_2 in the figure). The grid points on both axes are the same: $0, B^1, B^2, \ldots, B^N = D$, where B is the base number, N is the granularity factor (the number of bins on the axes) while D is the cell diameter (the maximum range).

After acquiring the approximated β angle in the first quadrant, we finally map it to its correct quadrant by checking the sign of a and b coordinates, giving us a direct indication of the UE's position in the other three quadrants as depicted in Figure 2. After this step, we obtain the approximated angle (α_1' and α_2') of the beam for the given UE that needs to be set. The angle information is then encapsulated into a beam configuration message and sent to the corresponding base station.

The implementation design of the Angle Approximation method in the data plane is shown in Figure 3. When a location message is received, it is parsed and the UE's location with information about the base station is stored in a new header instance (loc). The base station coordinates ($bs.x$, $bs.y$) are resolved by an exact match-action table (MAT), mapping some identifier of the base station (e.g., GTP-TEID, IP, etc.) to its absolute location. Since P4 language does not support high-level computations such as arctan and absolute value ($|x|$), we calculate the relative coordinates in the first quadrant ($m.a = |a|$,$m.b = |b|$) by comparing the coordinates of the



(a) Direct Angle of Arrival **(b) Base-angle Approximation on a Grid** **(c) Final Angle Transformation**

Figure 2: Key steps of beam angle approximation with an exponentially binned grid.

base station and the UE and subtracting the higher value from the lower using simple if-statements, we also define variables (*m.signa*, *m.signb*) to hold the signs of a and b, respectively. Note that in our implementation we involved extra MATs for these computations instead of a simple if-statement and comparison. The angle approximation then relies on two match-action tables. Table Angle Approximation does range matching on keys *m.a* and *m.b*. The table is filled with constant range entries representing the grid with exponential binning as shown in Figure 2b. Each entry represents a grid cell and the related action sets the cell centroid-based approximation of base-angle β. Note that this table requires the most resources and in most P4-programmable hardware it is mapped to Ternary Content Addressable Memory (TCAM). The required TCAM space is mainly affected by the desired angle-approximation accuracy as we will show in Section 3. As a last step, Table Final Angle Transformation is applied that matches on keys *m.signa*, *m.signb* to obtain the final angle approximation α'. For example, the exact matched value (1,0) of *m.signa* and *m.signb* respectively, indicates that the location of UE is in the second quadrant and therefore the action to obtain final α' results in $180 - \beta$ (in degrees). Finally, the location header is removed and the control header is added, filled and the packet is readdressed before deparsing and forwarding to the designated base station.

3 PROOF OF CONCEPT

We have implemented the proposed method in P4 using the TNA (Tofino Native Architecture) architecture model and evaluated it on a Tofino ASIC. During the evaluation we focus on three aspects: 1) The approximation error of MAT-based angle estimation with different granularity factors (number of bins (N=20,40,60 and 80), 2) the effect of moving UEs and non-zero control cycle delays on the method's accuracy, and 3) the relationship between the utilization of Tofino resources (stages, SRAM, TCAM memories) and the applied granularity factor N.

3.1 Approximation Error

Figure. 4 depicts the absolute error distribution of angle approximation for grids with different granularity (N=20, 40, 60 and 80) and for different cell diameters ranging from 200m to 1km. During this experiment, we have taken 100.000 UE locations uniformly at random within a specific diameter around a base station and computed the angle approximation error of our MAT-based method. We also assume that the user cannot be closer to the base station than five meters which hold in most outdoor scenarios.

One can observe that the applied grid granularity has a higher impact on the approximation error than the cell diameter. The maximum errors for cases N=20,40,60 and 80 are approx. 8, 5, 4 and 2.5 degrees respectively. From a practical point of view, larger errors require wider beams. In static cases, the beam needs to be two times wider than the maximum approximation error. For example, if the beam is 5 degrees wide and the error is at most 2.5 degrees, the system can ensure that the UE still remains within the beam. In addition to the empirical analysis, we can also show a theoretical bound on the error of the applied grid-based angle approximation.

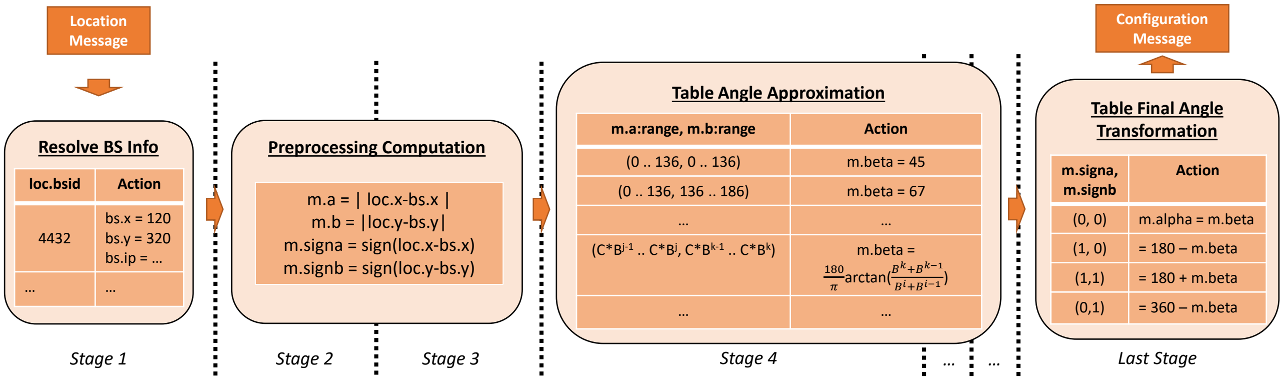
Lemma 1. *The absolute error of the proposed MAT-based angle approximation is bounded by* $2 \times \arctan(\sqrt{B}) - \frac{\pi}{2}$ *(in rads), where* B *is the base number in* $B^N = D$*, for a predefined maximum distance* D *and granularity factor* N*.*

Proof. (Proof sketch.) If the user's relative coordinates (a, b) lay in a cell grid $|a| \in [B^i, B^{(i+1)})$ and $|b| \in [B^k, B^{(k+1)})$ for any i, k positive integers. The angle is approximated according to the central point of the cell. The deviation from the real angle is the largest in one of the corner points of the cell. We can define the error functions for the corner points in this way and take the derivative in i and k to find the location of maximum errors. After that, we can get the error bound trivially. □

One can observe that this theoretical bound is in accordance with the above empirical error distributions. For example, in cell with diameter of 800 meters, the theoretical error bounds for granularity factors N=20,40,60 and 80 are 9.5, 4.8, 3.2 and 2.4 degrees respectively.

3.2 Moving UEs and Control Latency

To demonstrate our concept in a more dynamic scenario, we consider a small cell in a semi-urban environment located at the



Resolve BS Info

loc.bsid	Action
4432	bs.x = 120 bs.y = 320 bs.ip = ...
...	...

Preprocessing Computation

m.a = | loc.x-bs.x |
m.b = |loc.y-bs.y|
m.signa = sign(loc.x-bs.x)
m.signb = sign(loc.y-bs.y)

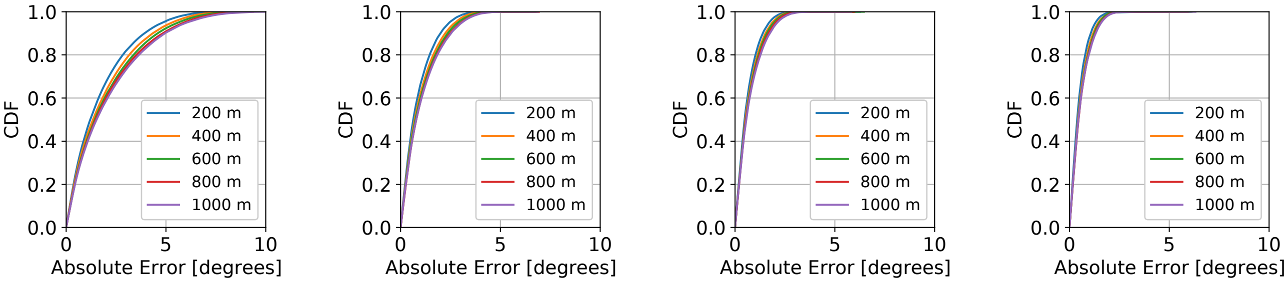
Table Angle Approximation

m.a:range, m.b:range	Action
(0 .. 136, 0 .. 136)	m.beta = 45
(0 .. 136, 136 .. 186)	m.beta = 67
...	...
$(C*B^{i-1} .. C*B^{i}, C*B^{k-1} .. C*B^{k})$	m.beta = $\frac{180}{\pi}\arctan(\frac{B^k+B^{k-1}}{B^i+B^{i-1}})$
...	...

Table Final Angle Transformation

m.signa, m.signb	Action
(0, 0)	m.alpha = m.beta
(1, 0)	= 180 – m.beta
(1,1)	= 180 + m.beta
(0,1)	= 360 – m.beta

Figure 3: Data Plane Design of the Angle Approximation



(a) N=20 (b) N=40 (c) N=60 (d) N=80

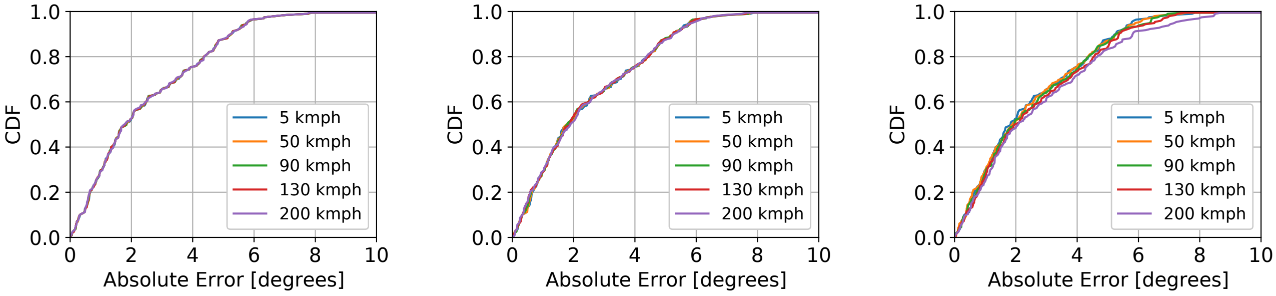
Figure 4: Error Distribution of MAT-based Angle Approximation.

Figure 5: University campus showing the transmitter and the mobile user.

campus of the University of Glasgow, UK. Figure 5 shows the base station, located on James Watt South (JWS) building in the campus. A user is assumed to be moving on a route at a constant speed through the scene shown as a red arrow. The route denoted covers the Byres Road, James McCune Smith (JMS), Library and Glasgow University Union (GUU). The user's constant speed is varied from 5 to 200kmph (pedestrian to high-speed trains). Note that we only emulate the movement of the UE in this scenario and evaluate the effect of displacement in the UE's location when the feedback loop of angle-approximation and beam reconfiguration requires more than zero time.

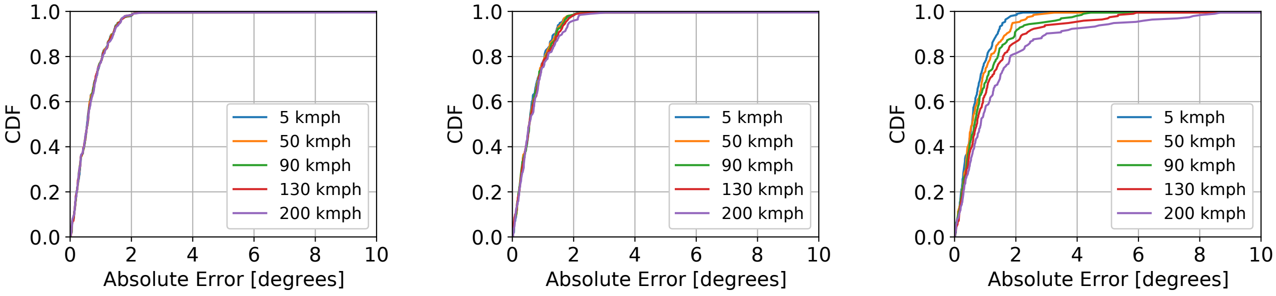
We assume that the UE periodically sends a location message to the P4-based angle approximation node that - as a result - generates a beam configuration message and forwards it to the corresponding base station. The round trip delay between the departure of the location information message from the UE and the arrival of control message to the base station is varied in a range of 5, 20 and 100ms. The angle approximation errors depicted in Figure. 6-7 were calculated at the time of arrival of the configuration message to the base station, thus it also takes the user's movement into account.

Figure. 6 and Figure. 7 prove that larger granularity factor (N) results in better angle approximation even when the control cycle is longer and the UE is moving at a moderate speed. Comparing the case of $N = 20$ to $N = 80$, one can see that the increase in the error caused by the latency and movement is less important for $N = 20$ when the base error is also high (around 9 degrees). The error distributions are similar to our static scenarios depicted in Figure. 4. The large deviance can only be seen when the control cycle time is 100ms and the UE moves fast (>90kmph), as depicted in Figure. 7c. It also indicates that at high speed wider beams are needed otherwise the UE can easily get out of the coverage as the beam cannot keep track of the UE. Note that a real-world environment is more complex where the radio propagation is influenced by many environmental factors, also affecting the UE's quality of experience.



(a) Control Cycle=5ms **(b) Control Cycle=20ms** **(c) Control Cycle=100ms**

Figure 6: Angle approximation error when the user moves at a constant speed and the control cycle is not zero. N is set to 20.



(a) Control Cycle=5ms **(b) Control Cycle=20ms** **(c) Control Cycle=100ms**

Figure 7: Angle approximation error when the user moves at a constant speed (5kmph to 200kmph) and the control cycle is 5ms, 20ms or 100ms. N is fixed to 80.

3.3 Resource Usage

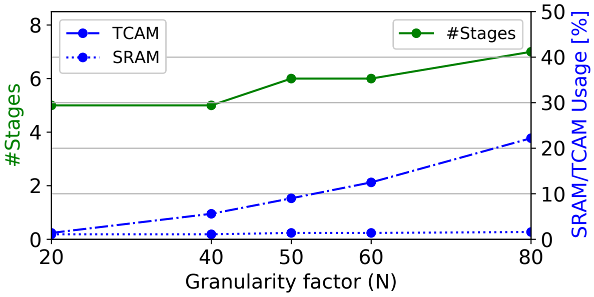


Figure 8: The trade-off between granularity factor (N) and resource usage (stages, SRAM and TCAM) on a Tofino ASIC.

We have shown in the previous sections that the grid resolution defined by the granularity factor N has the highest impact on the achievable angle approximation accuracy. A larger N results in better accuracy, but it requires a much larger TCAM space to implement the grid searching logic in MAT. Figure. 8 depicts the relationship between the applied granularity factor N and the number of required stages, SRAM and TCAM usage. One can observe that SRAM usage is almost constant and independent of the granularity factor. The grid-based angle approximation is implemented by a TCAM table and thus the granularity factor has a strong correlation with the required TCAM space. For $N = 20$ and 40, the TCAM table only occupies a single stage, for N=50 and 60 the TCAM table is distributed among two stages while in the case of N=80 three stages are required to store this table. Note that the per-stage TCAM space is limited. The number of stages is only affected by the size of the TCAM table. Though the proposed method occupies the TCAM space on one or more stages, its per-stage resource usage is not significant in general thus other network functions/pipelines (e.g., related to mobile transport or RAN) can also be co-located with the proposed pipeline. The TCAM space of stages implementing the MAT-based angle approximation table is in essence fully occupied, but other resources like SRAM and ALUs can potentially be used in these stages by other pipelines.

3.4 Customization

The surrounding around a base station may be different and thus radio propagation would not occur along a straight line because of, e.g., reflections from buildings and other objects. To handle these effects, the customization of the proposed method may be needed. Instead of applying the global model implemented by our Angle Approximation table, we could 1) introduce customized tables for each base station and 2) extend the angle approximation grid to all the possible quadrants around the base station, handling asymmetric signal propagation in the cell. In the latter case, the approximation table requires four times more TCAM entries for covering all the four quadrants of the cell. However, in the first case we need to create separate tables for each base station, multiplying the needed TCAM space. Our future work includes the more detailed analysis of customization scenarios and their efficient realization.

4 RELATED WORK

New ways have been explored like channel sounding [11] in which Synchronization signal block (SSB) and channel state information reference signal (CSI-RS) for 5G downlink transmissions in accordance with the New Radio (NR) technical specifications suggested by 3GPP has been extracted and SAGE algorithm has been used to estimate the channel parameters. Their work gives the hope to introduce location-aided beamforming if we are able to extract the channel parameters. Apart from this, recently [9] proposed P4 based In band telemetry (INT) fully integrated with UEs. Decentralized steering rules, such as those involving UE and specific switches, are made possible by the INT mechanism, which is built to deliver synchronized and precise end-to-end latency and geolocation information without the need for software-defined radio (SDN) controller intervention. They also incorporate a forecast system helped by artificial intelligence that can anticipate latency and localization in advance and initiate faster edge steering.

Both these works are giving motivation that in future for more 5G communications operations, such as mmWave communications, which is being developed, and vehicle to everything (V2X), which was recently added in the 3GPP technical specification [1], will be commercially accessible. Then we can use the proposed frameworks enabling location-assisted beamforming.

Our proposed solution is to establish a direct link between UE and base station so that BS that consists of an advanced antenna system can direct the signal or beam in the direction of arrival from the user.

5 CONCLUSION

The estimation of the direction of arrival is crucial to any adaptive beamforming strategy in wireless communications. Conventionally, beamforming algorithms run at the link layer of the network and this introduces additional latency when backhaul networks are considered. With a view to making the networks more responsive, we have proposed a new user-assisted beamforming strategy that exploits the advantages of programmable data planes and in-network computation using P4. Accordingly, the user equipment (UE) periodically reports its location to the network and the computation of beam parameters (the angle of arrival in this paper) are done by one of the programmable switches inside the network. Our preliminary results show that the additional computation performed to divide the cell area into binned grid provides angle approximations with error bounds and requires moderate per-stage resources. The proposed scheme was also demonstrated on a Tofino ASIC.

As part of our future work, we aim to integrate the P4-based angle approximation with a realistic radio propagation simulator, enabling us to quantify the effect of our method on channel quality seen by the UE. We also will investigate how our generalized model can efficiently be customized so that we could take into account the differences in the base stations’ surroundings (e.g., buildings and other obstacles influencing the signal propagation) without significantly increasing the required TCAM space.

ACKNOWLEDGMENT

The research was supported by the SICSA Saltire Emerging Researcher Scheme and the National Research, Development and Innovation Office – NKFIH, FK 138949.

REFERENCES

[1] 3GPP. 2018. NR; Physical channels and modulation. *3rd Generation Partnership Project (3GPP), Technical Specification (TS) 38.211* 9 (2018).

[2] Frederik Hauser, Marco Häberle, Daniel Merling, Steffen Lindner, Vladimir Gurevich, Florian Zeiger, Reinhard Frank, and Michael Menth. 2021. A survey on data plane programming with p4: Fundamentals, advances, and applied research. *arXiv preprint arXiv:2101.10632* (2021).

[3] Enio Kaljic, Almir Maric, Pamela Njemcevic, and Mesud Hadzialic. 2019. A survey on data plane flexibility and programmability in software-defined networking. *IEEE Access* 7 (2019), 47804–47840.

[4] Sukhveer Kaur, Krishan Kumar, and Naveen Aggarwal. 2021. A review on P4-Programmable data planes: Architecture, research efforts, and future directions. *Computer Communications* 170 (2021), 109–129.

[5] Mehdi M Molu, Pei Xiao, Mohsen Khalily, Kanapathippillai Cumanan, Lei Zhang, and Rahim Tafazolli. 2017. Low-complexity and robust hybrid beamforming design for multi-antenna communication systems. *IEEE Transactions on Wireless Communications* 17, 3 (2017), 1445–1459.

[6] Francesco Paolucci, Filippo Cugini, Piero Castoldi, and Tomasz Osiński. 2021. Enhancing 5G SDN/NFV edge with P4 data plane programmability. *IEEE Network* 35, 3 (2021), 154–160.

[7] Theodore S Rappaport, Shu Sun, Rimma Mayzus, Hang Zhao, Yaniv Azar, Kevin Wang, George N Wong, Jocelyn K Schulz, Mathew Samimi, and Felix Gutierrez. 2013. Millimeter wave mobile communications for 5G cellular: It will work! *IEEE access* 1 (2013), 335–349.

[8] Wonil Roh, Ji-Yun Seol, Jeongho Park, Byunghwan Lee, Jaekon Lee, Yungsoo Kim, Jaeweon Cho, Kyungwhoon Cheun, and Farshid Aryanfar. 2014. Millimeter-wave beamforming as an enabling technology for 5G cellular communications: Theoretical feasibility and prototype results. *IEEE communications magazine* 52, 2 (2014), 106–113.

[9] Davide Scano, Francesco Paolucci, Koteswararao Kondepu, Andrea Sgambelluri, Luca Valcarenghi, and Filippo Cugini. 2021. Extending P4 in-band telemetry to user equipment for latency-and localization-aware autonomous networking with AI forecasting. *Journal of Optical Communications and Networking* 13, 9 (2021), D103–D114.

[10] Shree Krishna Sharma, Tadilo Endeshaw Bogale, Long Bao Le, Symeon Chatzinotas, Xianbin Wang, and Björn Ottersten. 2017. Dynamic spectrum sharing in 5G wireless networks with full-duplex technology: Recent advances and research challenges. *IEEE Communications Surveys & Tutorials* 20, 1 (2017), 674–707.

[11] Tianqi Wu, Xuefeng Yin, Linjian Zhang, and Jie Ning. 2021. Measurement-based channel characterization for 5G downlink based on passive sounding in sub-6 GHz 5G commercial networks. *IEEE Transactions on Wireless Communications* 20, 5 (2021), 3225–3239.

[12] Xianyue Wu, Cheng-Xiang Wang, Jian Sun, Jie Huang, Rui Feng, Yang Yang, and Xiaohu Ge. 2017. 60-GHz millimeter-wave channel measurements and modeling for indoor office environments. *IEEE Transactions on Antennas and Propagation* 65, 4 (2017), 1912–1924.

[13] Ming Xiao, Shahid Mumtaz, Yongming Huang, Linglong Dai, Yonghui Li, Michail Matthaiou, George K Karagiannidis, Emil Björnson, Kai Yang, I Chih-Lin, et al. 2017. Millimeter wave communications for future mobile networks. *IEEE Journal on Selected Areas in Communications* 35, 9 (2017), 1909–1935.

[14] Xuan Xue, Yongchao Wang, Xianbin Wang, and Tadilo Endeshaw Bogale. 2016. Joint source and relay precoding in multiantenna millimeter-wave systems. *IEEE Transactions on Vehicular Technology* 66, 6 (2016), 4924–4937.

[15] Kegen Yu and Y Jay Guo. 2008. Statistical NLOS identification based on AOA, TOA, and signal strength. *IEEE Transactions on Vehicular Technology* 58, 1 (2008), 274–286.