Article

Not peer-reviewed version

Minimization of Bandwidth for Required End-to-End Latency Implementing IRS in a 6G Network

Mobasshir Mahbub * and Raed M. Shubair

Posted Date: 3 July 2024

doi: 10.20944/preprints202407.0297.v1

Keywords: 6G; IRS; HetNet

Article

Minimization of Bandwidth for Required End-to-End Latency Implementing IRS in a 6G Network

Mobasshir Mahbub * and Raed M. Shubair

New York University Abu Dhabi
* Correspondence: mbsrmhb@gmail.com

Abstract: The goal of the investigation is to increase coverage, which is ensure better transmission around IoT services using IRS within a two-tier 6G system comprising of one micro cell tier running beneath a macro cellular tier. As a result, the study tested and compared the reliability of traditional connectivity with IRS-enhanced connectivity in terms of upstream end-to-end latency using computer-based measuring methods. The study concluded that the implementation of IRS greatly improves coverage, which means transmission effectiveness, for 6G services.

Keywords: 6G; IRS; HetNet

1. Introduction

With the widespread commercial use of 5th Gen (5G) mobile networks, the Internet of Things usage possibilities have expanded. From 2nd Gen (2G) to 5G, networking resource optimization is critical for mobile communication success [1–4]. Nevertheless, wireless communications are reaching Shannon limitations, and the current resources are insufficient [5–9]. Contrary to the 5G wireless communication system, the next level (6G) communication system offers a greater coverage, allowing for integrated interconnection of satellite, sky, the surface, and water. Some novel resource optimization measures must be used to guarantee Quality of Service (also called QoS) in 6G systems [10–13].

The 6G system is envisioned as expansive, with ambitious future goals. It is projected to deliver intelligently enabled seamless connection everywhere while consuming less energy, hence improving society and quality of life overall. The growing need for connecting gadgets and internet traffic is the primary driving reason behind the need for 6G advancement [14–19]. The primary driving and expected developments regarding 6G are exceptionally high data speeds of 1Tbps, incredibly low latency (a tenth of 5G), 50 times quicker than 5G, 2x greater energy efficiency, along with 2x higher spectrum efficiency [20–24]. The standard organizations, especially the International Telecommunications Union-Radio Communications Sector (ITU-R), demonstrated the cutting edge of 6G activity by 2030 on the basis of quantity as well as quality for the modern era, predicting that mobile data usage will surpass the limit of greater than 5ZB per monthly [25–30]. Other properties of a 6G wireless communication system include better dependability, new spectrum, excellent network availability, cognitive networking, sustainable communication, computation, location, control, green connectivity, and monitoring [31–36]. The 6G flagship-based initiatives (like 6Genesis) have already begun to target sophisticated technology. The primary characteristics consist of a delay of less than 0.1ms in the user's device plane along with 1ms in the command plane, downlink spectral accuracy of 100bps/Hz or further, the operation in the sub-terahertz as well as terahertz groups, expected data rates of approximately 1Tbps, as well as battery-free IoT appliances [37–43]. The network's reach has been increased by using various technology integrations including satellite and terrestrial networks

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 3 July 2024 doi:10.20944/preprints202407.0297.v1

[44–49]. The 6G network is projected to provide native intelligence, increased spectrum efficiency, and worldwide coverage. The notion of cognitive intelligence in 6G, manifested as decision-making, has cleared the path for the growth of communication networks. Multitude large-scale executions are predicted as a result of 6G network technology. In terms of programs, the 6G network may accommodate high-end data rate services such as virtual reality, augmented reality, unified reality, 3D visualization, implants, internet of medical things, autonomous driving, sensing, and the network of intelligent applications [50–57].

6G cellular networks must have THz interactions, intelligently reflecting surfaces (IRS), holographic multi-input multi-output (HMIMO), symbiotic radio, multi-tier heterogeneous networks, cell-free network connectivity, and so on [58–63]. Furthermore, it is anticipated that 6G will include an artificial intelligence-based cloud-edge-device collaborative ground-air-space interconnected ecosystem [64–70].

Global wireless networks, especially in metropolitan areas, have become increasingly diverse in recent years in order to handle exponentially expanding traffic data [71–77]. Wireless mobile networks that comprise base stations with diverse features are unbalanced, and such BSs function independently [78–82]. Cross-tier disturbance has a significant negative impact on system performance. As a result, collaboration across diverse BSs and the blending of heterogeneous networking is a pressing issue in next-generation networks [83–89].

An IRS constitutes a rectangular metasurface composed of a large number of reflecting elements that has lately received academic interest for its capacity to dramatically increase the energy and spectrum efficiency of communication systems by changing wireless transmission circumstances [90–94]. IRS components can reflect the arriving signal with the appropriate phase shift. IRS continually alters the propagation of the reflecting signal, resulting in constructive signals combination and destructive noise suppression by the receiving device. As a consequence, QoS can be enhanced at the receiving end [95,96].

As a result, the research compared the performance of traditional micro cellular connectivity to IRS-based micro cellular connectivity in terms of upstream end-to-end latency.

2. Related Literature

The feasibility and efficacy of employing IRSs in 6G-based recognizing has just been examined in research [97–99]. Several studies have looked into ways to use IRSs as anchoring for localization within the context of device-based sensing. The study [100] examined an angle-based localization mechanism made up of a BS, numerous IRSs, and user devices. To solve the maximum probability problem for determining angle details, a two-step technique was proposed. Initially an exhaustive search approach is implemented throughout a discrete structure to find a few favorable initial points, following which a gradient decent hunt method is used to find a more effective angle approach. The user may then be localized using its angles to various anchors, such as the BS along with IRSs.

3. Measurement Model

3.1. IRS-Based Model

The power for IRS-powered cell is measured by (Equation (1)) [101],

$$P_{rec}^{UL(irs)} = p_{tr}^{UL(irs)} \frac{l_x l_y G_{st} \lambda^2 cos(\theta_{tr}) cos(\theta_{rec}) A^2 g_{tr} g_{rec} {T_{tr}}^2 {R_{rec}}^2}{(m_1 m_2)^2 (4\pi)^3} \tag{1}$$

where $G_{st} = \frac{4\pi d_x d_y}{\lambda^2}$ represents the IRS dispersion gain. l_x and l_y express the IRS's structures. θ_{tr} and θ_{rec} describe the broadcast and reception angles. A denotes the reflection factor. g_{tr} and g_{rec} represent the transmit and receive amplification gain. T_{tr} and R_{rec} are the aggregate amount of the transmitter and receiver components. $m_1 = \sqrt{(x^{Ue} - x^{irs})^2 + (y^{Ue} - y^{irs})^2 + (z^{Ue} - z^{irs})^2}$ indicates the space between the transmission gadget at (x^{Ue}, y^{Ue}, z^{Ue}) the IRS positioned at $(x^{irs}, y^{irs}, z^{irs})$ coordinates. $m_2 = \sqrt{(x^{irs} - x^{mc})^2 + (y^{irs} - y^{mc})^2 + (z^{irs} - z^{mc})^2}$ indicate the space across the IRS along with the base station situated at (x^{mc}, y^{mc}, z^{mc}) coordinates.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 3 July 2024 doi:10.20944/preprints202407.0297.v1

The upstream throughput in the case of IRS model is determined by (Equation (2)),

$$Tr^{UL(irs)} = BW\ log_2\left(1 + \frac{P_{rec}^{UL(irs)}}{int + G_{wn}}\right) \tag{2}$$

where int indicates the interference and G_{wn} denotes the noise and.

The transmission delay in uplink is derived by the equation below (Equation (3)),

$$\eth^{UL(irs)} = \frac{Uplink\ Data\ Size}{Tr^{UL(irs)}} \tag{3}$$

3.2. Conventional Model

The upward power can be measured by (Equation (4)) [102],

$$P_{rec}^{UL(C)} = p_{tr}^{UL(C)} \frac{\lambda^2}{z^{\alpha}(4\pi)^2} \tag{4}$$

where $z = \sqrt{(x^{Ue} - x^{mc})^2 + (y^{Ue} - y^{mc})^2 + (z^{Ue} - z^{mc})^2}$ indicate the spacing between the transmitting equipment and the base stations. $\lambda = c/f_c$ specifies the spectral length of the stream. f_c specify the bandwidth in Hz. c demonstrates the apparent velocity of light in ms^{-1}. α specifies the factor influencing the loss.

The upstream spectral efficiency equation is stated as follows (Equation (5)),

$$Tr^{UL(C)} = BW\ log_2\left(1 + \frac{P_{rec}^{UL(C)}}{int + G_{wn}}\right) \tag{5}$$

The transmission delay is derived by (Equation (6)),

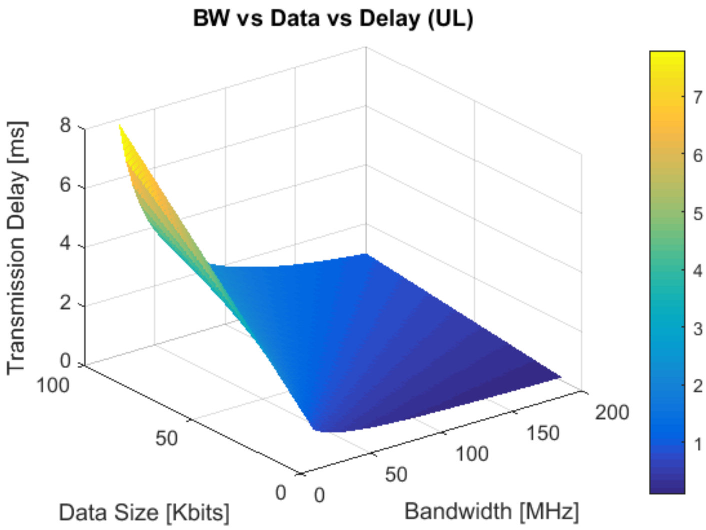
$$\eth^{UL(C)} = \frac{Uplink\ Data\ Size}{Tr^{UL(C)}} \tag{6}$$

4. Results and Discussions

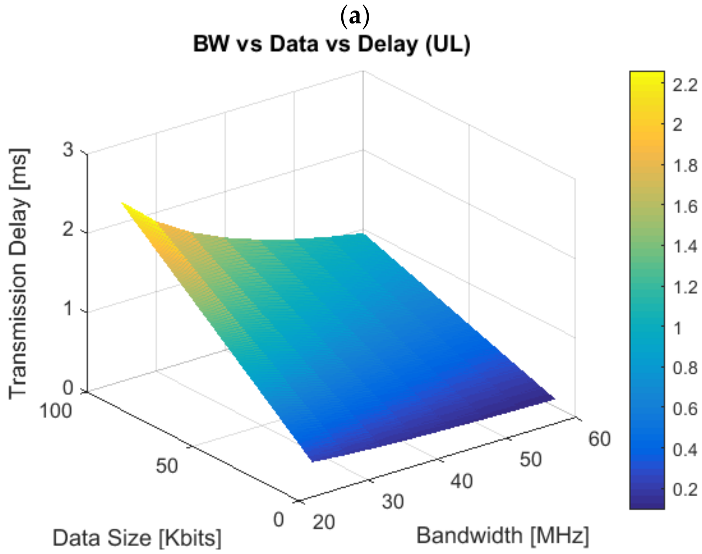
The study includes the measurement results obtained by using MATLAB-based calculations to implement the assessment approach, as well as evaluations of the result findings.

Figure 1a shows the measurement result of transmission delay in terms of bandwidth and data size in the context of cell-edge devices. Figure 1b illustrates the result of transmission delay in terms of bandwidth (reduced i.e., 60 MHz) and data size (100 Kb) when the transmitter-receiver separation distance is 50 m. Figure 1c visualizes the measurement of transmission delay in terms of bandwidth (maximum i.e., 200 MHz) and data size (increased i.e., 350 Kb) when the transmitter-receiver separation distance is 50 m. Figure 1d represents the uplink transmission delay considering the coverage region (200 MHz of bandwidth and 100 Kb of data size).

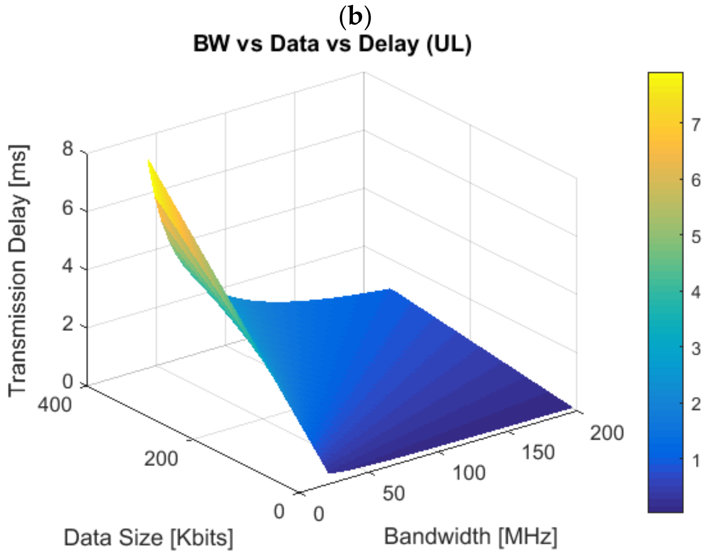
Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 3 July 2024 doi:10.20944/preprints202407.0297.v1



(a)

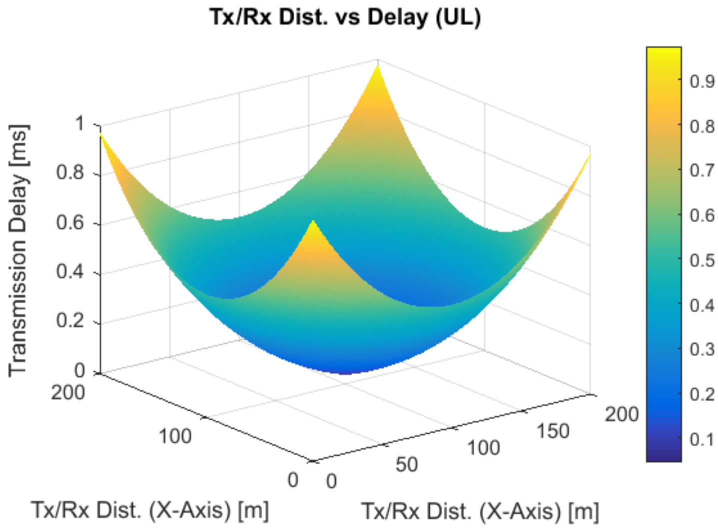


(b)



(c)

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 3 July 2024 doi:10.20944/preprints202407.0297.v1

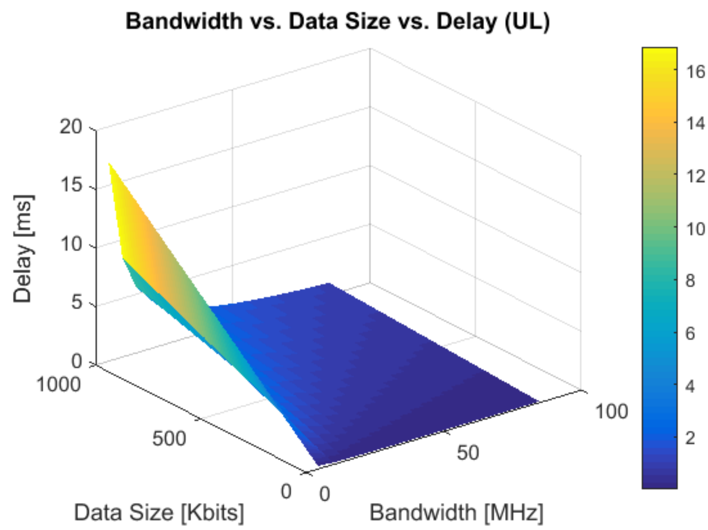


(**d**)

Figure 1. (a) Bandwidth vs. data size vs. transmission delay in uplink (IoTD at 100 m dist.), (b) Bandwidth vs. data size vs. transmission delay in uplink (IoTD at 50 m dist. and reduced bandwidth), (c) Bandwidth vs. data size vs. transmission delay in uplink (IoTD at 50 m dist. and maximum bandwidth), (d) Transmitter-receiver separation (3D) vs. transmission delay (non-IRS).

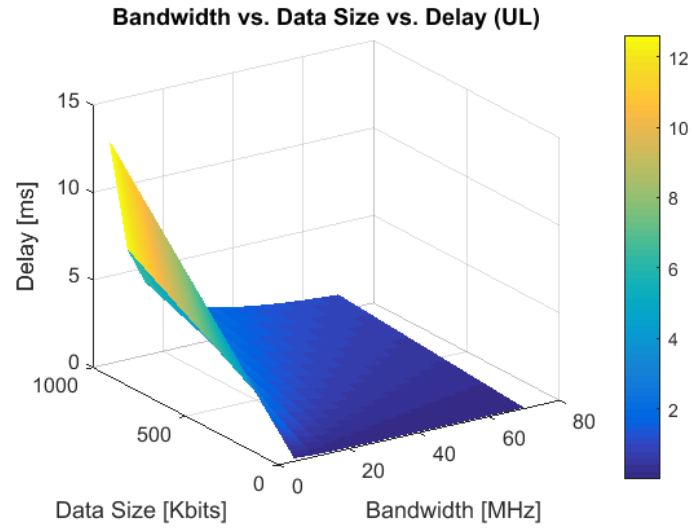
According to the specification or the requirement of 6G less than 1 ms end-to-end delay is required for the applications and services. At least 200 MHz bandwidth is required to offload data of size 100 Kb within 1 ms end-to-end delay when the IoT devices are 100 m away from the base station as per Figure 1a. When the devices are 50 m away from the base station at least 60 MHz bandwidth is required to offload data of size 100 Kb within 1 ms delay according to Figure 1b and with the maximum bandwidth (200 MHz) 350 Kb of data can be offloaded within 1 ms end-to-end delay as per Figure 1c. Figure 1d represents the 3D coverage region and delay for the maximum data size and bandwidth for better realization from which it can be realized that with a shorter transmitter-receiver separation the end-to-end delay requirement can be obtained with a lower amount of bandwidth.

Figure 2a,b visualize the uplink end-to-end transmission delay in terms of bandwidth and data with the varied number of Tx-Rx elements of IRS (for cell-edge devices). Figure 2c represents the uplink transmission delay considering the coverage region (85 MHz of bandwidth and 1000 Kb of data size).

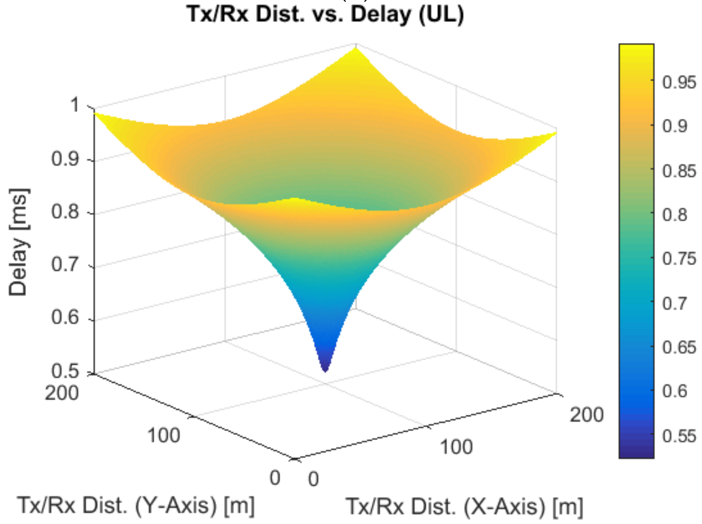


(**a**)

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 3 July 2024 doi:10.20944/preprints202407.0297.v1



(b)



(c)

Figure 2. (a) Bandwidth vs. data vs. transmission delay (128x128 Tx-Rx elements and IRS placed at 100 m away from IoTD), (b) Bandwidth vs. data vs. transmission delay (256x256 Tx-Rx elements and IRS placed at 100 m away from IoTD), (c) Transmitter-receiver separation vs. delay(128x128 Tx-Rx elements, data size 1000 Kb, 85 MHz bandwidth).

Analyzing Figure 2a,b it is evident that with the increase in the number of transmit-receive elements the required end-to-end latency is achieved with a reduced amount of bandwidth. 85 MHz bandwidth is required to offload 1000 Kb of data when the number of transmit-receive elements in 128x128 and when the number of transmit-receive elements gets increased to 256x256 70 MHz bandwidth is enough to offload 1000 Kb of data within 1 ms end-to-end delay. The end-to-end transmission delay in the case of uplink for the 3D coverage region is better realized in Figure 2c.

With the adoption of IRS the required end-to-end transmission delay can be achieved with a lower amount of bandwidth even if the data size is high. In the case of the conventional communication model maximum allowable 200 MHz bandwidth can offload up to 100 Kb of data and in the case of the IRS-assisted model, only 85 MHz bandwidth is required to offload 1000 Kb (considered maximum data size) of data within the end-to-end delay of less than 1 ms (if the number of transmit-receive elements of the IRS raised the required end-to-end delay can be obtained even with a lower amount of bandwidth).

5. Conclusion

The project aimed to improve access to services within the context of upcoming 6G networks by combining IRS onto a micro cell underlying a two-tier system that functions at the macro cell-level. A literature evaluation of relevant present investigations was conducted to provide perspective and identify research limitations or gaps. It developed a measuring model for conventional and IRS-aided micro-cell infrastructure, as well as formulas for calculating uplink throughput. According to the experiments, IRS-aided micro-cell networks outperform typical non-IRS microcell networking. Furthermore, an IRS-aided infrastructure conserves energy by reducing transmission power.

Declaration of Competing Interest: The authors declare no known competing interests.

References

1. Nishtha Chopra, Mike Phipott, Akram Alomainy, Qammer H. Abbasi, Khalid Qaraqe, and Raed M. Shubair. "THz time domain characterization of human skin tissue for nano-electromagnetic communication." In 2016 16th Mediterranean Microwave Symposium (MMS), pp. 1-3. IEEE, 2016.
2. Mohamed I. AlHajri, Nazar T. Ali, and Raed M. Shubair. "Classification of indoor environments for IoT applications: A machine learning approach." IEEE Antennas and Wireless Propagation Letters 17, no. 12 (2018): 2164-2168.
3. Mohamed I. AlHajri, Nazar T. Ali, and Raed M. Shubair. "Indoor localization for IoT using adaptive feature selection: A cascaded machine learning approach." IEEE Antennas and Wireless Propagation Letters 18, no. 11 (2019): 2306-2310.
4. M. I. AlHajri, A. Goian, M. Darweesh, R. AlMemari, R. M. Shubair, L. Weruaga, and A. R. Kulaib. "Hybrid RSS-DOA technique for enhanced WSN localization in a correlated environment." In 2015 International Conference on Information and Communication Technology Research (ICTRC), pp. 238-241. IEEE, 2015.
5. M. A. Al-Nuaimi, R. M. Shubair, and K. O. Al-Midfa. "Direction of arrival estimation in wireless mobile communications using minimum variance distortionless response." In The Second International Conference on Innovations in Information Technology (IIT'05), pp. 1-5. 2005.
6. Menna El Shorbagy, Raed M. Shubair, Mohamed I. AlHajri, and Nazih Khaddaj Mallat. "On the design of millimetre-wave antennas for 5G." In 2016 16th Mediterranean Microwave Symposium (MMS), pp. 1-4. IEEE, 2016.
7. Fahad Belhoul, Raed M. Shubair, and Mohammed E. Al-Mualla. "Modelling and performance analysis of DOA estimation in adaptive signal processing arrays." In ICECS, pp. 340-343. 2003.
8. Ahmed A. Ibrahim, Jan Machac, and Raed M. Shubair. "Compact UWB MIMO antenna with pattern diversity and band rejection characteristics." Microwave and Optical Technology Letters 59, no. 6 (2017): 1460-1464.
9. Ali Hakam, Raed M. Shubair, and Ehab Salahat. "Enhanced DOA estimation algorithms using MVDR and MUSIC." In 2013 International Conference on Current Trends in Information Technology (CTIT), pp. 172-176. IEEE, 2013.
10. M. Saeed Khan, A-D. Capobianco, Sajid M. Asif, Adnan Iftikhar, Benjamin D. Braaten, and Raed M. Shubair. "A pattern reconfigurable printed patch antenna." In 2016 IEEE International Symposium on Antennas and Propagation (APSURSI), pp. 2149-2150. IEEE, 2016.
11. Ebrahim M. Al-Ardi, \Raed M. Shubair, and Mohammed E. Al-Mualla. "Direction of arrival estimation in a multipath environment: An overview and a new contribution." Applied Computational Electromagnetics Society Journal 21, no. 3 (2006): 226.
12. M. Saeeed Khan, Adnan Iftikhar, Sajid M. Asif, Antonio-Daniele Capobianco, and Benjamin D. Braaten. "A compact four elements UWB MIMO antenna with on-demand WLAN rejection." Microwave and Optical Technology Letters 58, no. 2 (2016): 270-276.
13. R. M. Shubair. "Robust adaptive beamforming using LMS algorithm with SMI initialization." In 2005 IEEE Antennas and Propagation Society International Symposium, vol. 4, pp. 2-5. IEEE, 2005.
14. Muhammad Saeed Khan, Adnan Iftikhar, Antonio-Daniele Capobianco, Raed M. Shubair, and Bilal Ijaz. "Pattern and frequency reconfiguration of patch antenna using PIN diodes." Microwave and Optical Technology Letters 59, no. 9 (2017): 2180-2185.
15. R. M. Shubair and A. Al-Merri. "Robust algorithms for direction finding and adaptive beamforming: performance and optimization." In The 2004 47th Midwest Symposium on Circuits and Systems, 2004. MWSCAS'04., vol. 2, pp. II-II. IEEE, 2004.
16. Muhammad Saeed Khan, Adnan Iftikhar, Antonio-Daniele Capobianco, Raed M. Shubair, and Bilal Ijaz. "Pattern and frequency reconfiguration of patch antenna using PIN diodes." Microwave and Optical Technology Letters 59, no. 9 (2017): 2180-2185.

17. Pradeep Kumar Singh, Bharat K. Bhargava, Marcin Paprzycki, Narottam Chand Kaushal, and Wei-Chiang Hong, eds. Handbook of wireless sensor networks: issues and challenges in current Scenario's. Vol. 1132. Berlin/Heidelberg, Germany: Springer, 2020.
18. Muhammad Saeed Khan, Adnan Iftikhar, Raed M. Shubair, Antonio-D. Capobianco, Benjamin D. Braaten, and Dimitris E. Anagnostou. "Eight-element compact UWB-MIMO/diversity antenna with WLAN band rejection for 3G/4G/5G communications." IEEE Open Journal of Antennas and Propagation 1 (2020): 196-206.
19. R. M. Shubair and Y. L. Chow. "A closed-form solution of vertical dipole antennas above a dielectric half-space." IEEE transactions on antennas and propagation 41, no. 12 (1993): 1737-1741.
20. Amjad Omar, and Raed Shubair. "UWB coplanar waveguide-fed-coplanar strips spiral antenna." In 2016 10th European Conference on Antennas and Propagation (EuCAP), pp. 1-2. IEEE, 2016.
21. Ebrahim M. Al-Ardi, Raed M. Shubair, and Mohammed E. Al-Mualla. "Computationally efficient DOA estimation in a multipath environment using covariance differencing and iterative spatial smoothing." In 2005 IEEE International Symposium on Circuits and Systems, pp. 3805-3808. IEEE, 2005.
22. Malak Y. ElSalamouny, and Raed M. Shubair. "Novel design of compact low-profile multi-band microstrip antennas for medical applications." In 2015 loughborough antennas & propagation conference (LAPC), pp. 1-4. IEEE, 2015.
23. E. M. Al-Ardi, R. M. Shubair, and M. E. Al-Mualla. "Investigation of high-resolution DOA estimation algorithms for optimal performance of smart antenna systems." (2003): 460-464.
24. Raed M. Shubair and Hadeel Elayan. "In vivo wireless body communications: State-of-the-art and future directions." In 2015 Loughborough Antennas & Propagation Conference (LAPC), pp. 1-5. IEEE, 2015.
25. Raed M. Shubair, Amna M. AlShamsi, Kinda Khalaf, and Asimina Kiourti. "Novel miniature wearable microstrip antennas for ISM-band biomedical telemetry." In 2015 Loughborough Antennas & Propagation Conference (LAPC), pp. 1-4. IEEE, 2015.
26. E. M. Al-Ardi, Raed M. Shubair, and M. E. Al-Mualla. "Performance evaluation of direction finding algorithms for adapative antenna arrays." In 10th IEEE International Conference on Electronics, Circuits and Systems, 2003. ICECS 2003. Proceedings of the 2003, vol. 2, pp. 735-738. IEEE, 2003.
27. Hadeel Elayan, Raed M. Shubair, and Asimina Kiourti. "Wireless sensors for medical applications: Current status and future challenges." In 2017 11th European Conference on Antennas and Propagation (EUCAP), pp. 2478-2482. IEEE, 2017.
28. Ala Eldin Omer, George Shaker, Safieddin Safavi-Naeini, Georges Alquié, Frédérique Deshours, Hamid Kokabi, and Raed M. Shubair. "Non-invasive real-time monitoring of glucose level using novel microwave biosensor based on triple-pole CSRR." IEEE Transactions on Biomedical Circuits and Systems 14, no. 6 (2020): 1407-1420.
29. M. I. AlHajri, N. Alsindi, N. T. Ali, and R. M. Shubair. "Classification of indoor environments based on spatial correlation of RF channel fingerprints." In 2016 IEEE international symposium on antennas and propagation (APSURSI), pp. 1447-1448. IEEE, 2016.
30. Raed M. Shubair and Hadeel Elayan. "In vivo wireless body communications: State-of-the-art and future directions." In 2015 Loughborough Antennas & Propagation Conference (LAPC), pp. 1-5. IEEE, 2015.
31. Muhammad S. Khan, Syed A. Naqvi, Adnan Iftikhar, Sajid M. Asif, Adnan Fida, and Raed M. Shubair. "A WLAN band-notched compact four element UWB MIMO antenna." International Journal of RF and Microwave Computer-Aided Engineering 30, no. 9 (2020): e22282.
32. Mohamed AlHajri, Abdulrahman Goian, Muna Darweesh, Rashid AlMemari, Raed Shubair, Luis Weruaga, and Ahmed AlTunaiji. "Accurate and robust localization techniques for wireless sensor networks." arXiv preprint arXiv:1806.05765 (2018).
33. Hadeel Elayan, Raed M. Shubair, and Asimina Kiourti. "Wireless sensors for medical applications: Current status and future challenges." In 2017 11th European Conference on Antennas and Propagation (EUCAP), pp. 2478-2482. IEEE, 2017.
34. Saad Alharbi, Raed M. Shubair, and Asimina Kiourti. "Flexible antennas for wearable applications: Recent advances and design challenges." (2018): 484-3.
35. Goian, Mohamed I. AlHajri, Raed M. Shubair, Luis Weruaga, Ahmed Rashed Kulaib, R. AlMemari, and Muna Darweesh. "Fast detection of coherent signals using pre-conditioned root-MUSIC based on Toeplitz matrix reconstruction." In 2015 IEEE 11th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), pp. 168-174. IEEE, 2015.
36. Hadeel Elayan, Raed M. Shubair, Josep Miquel Jornet, and Raj Mittra. "Multi-layer intrabody terahertz wave propagation model for nanobiosensing applications." Nano communication networks 14 (2017): 9-15.
37. M. S. Khan, F. Rigobello, Bilal Ijaz, E. Autizi, A. D. Capobianco, R. Shubair, and S. A. Khan. "Compact 3-D eight elements UWB-MIMO array." Microwave and Optical Technology Letters 60, no. 8 (2018): 1967-1971.

38. Raed M. Shubair, and Ali Hakam. "Adaptive beamforming using variable step-size LMS algorithm with novel ULA array configuration." In 2013 15th IEEE International Conference on Communication Technology, pp. 650-654. IEEE, 2013.
39. Hadeel Elayan, Pedram Johari, Raed M. Shubair, and Josep Miquel Jornet. "Photothermal modeling and analysis of intrabody terahertz nanoscale communication." IEEE transactions on nanobioscience 16, no. 8 (2017): 755-763.
40. R. Karli, H. Ammor, R. M. Shubair, M. I. AlHajri, and A. Hakam. "Miniature Planar Ultra-Wide-Band Microstrip Patch Antenna for Breast Cancer Detection." Skin 1 (2016): 39.
41. R. M. Shubair, and A. Merri. "Convergence of adaptive beamforming algorithms for wireless communications." In Proc. IEEE and IFIP International Conference on Wireless and Optical Communications Networks, pp. 6-8. 2005.
42. Rui Zhang, Ke Yang, Akram Alomainy, Qammer H. Abbasi, Khalid Qaraqe, and Raed M. Shubair. "Modelling of the terahertz communication channel for in-vivo nano-networks in the presence of noise." In 2016 16th Mediterranean Microwave Symposium (MMS), pp. 1-4. IEEE, 2016.
43. Mohammed S Al-Basheir, Raed M Shubai, and Sami M. Sharif. "Measurements and analysis for signal attenuation through date palm trees at 2.1 GHz frequency." (2006).
44. Zhenghua Chen, Mohamed I. AlHajri, Min Wu, Nazar T. Ali, and Raed M. Shubair. "A novel real-time deep learning approach for indoor localization based on RF environment identification." IEEE Sensors Letters 4, no. 6 (2020): 1-4.
45. Samar Elmeadawy and Raed M. Shubair. "6G wireless communications: Future technologies and research challenges." In 2019 international conference on electrical and computing technologies and applications (ICECTA), pp. 1-5. IEEE, 2019.
46. Ala Eldin Omer, George Shaker, Safieddin Safavi-Naeini, Kieu Ngo, Raed M. Shubair, Georges Alquié, Frédérique Deshours, and Hamid Kokabi. "Multiple-cell microfluidic dielectric resonator for liquid sensing applications." IEEE Sensors Journal 21, no. 5 (2020): 6094-6104.
47. R. M. Shubair, A. Merri, and W. Jessmi. "Improved adaptive beamforming using a hybrid LMS/SMI approach." In Second IFIP International Conference on Wireless and Optical Communications Networks, 2005. WOCN 2005., pp. 603-606. IEEE, 2005.
48. Maryam AlNabooda, Raed M. Shubair, Nadeen R. Rishani, and GhadahAldabbagh. "Terahertz spectroscopy and imaging for the detection and identification of illicit drugs." 2017 Sensors networks smart and emerging technologies (SENSET) (2017): 1-4.
49. Muhammad Saeed Khan, Adnan Iftikhar, Raed M. Shubair, Antonio-Daniele Capobianco, Sajid Mehmood Asif, Benjamin D. Braaten, and Dimitris E. Anagnostou. "Ultra-compact reconfigurable band reject UWB MIMO antenna with four radiators." Electronics 9, no. 4 (2020): 584.
50. Mohamed I. AlHajri, Nazar T. Ali, and Raed M. Shubair. "A machine learning approach for the classification of indoor environments using RF signatures." In 2018 IEEE Global Conference on Signal and Information Processing (GlobalSIP), pp. 1060-1062. IEEE, 2018.
51. Hadeel Elayan, Raed M. Shubair, and Asimina Kiourti. "On graphene-based THz plasmonic nano-antennas." In 2016 16th mediterranean microwave symposium (MMS), pp. 1-3. IEEE, 2016.
52. Amjad Omar, Maram Rashad, Maryam Al-Mulla, Hussain Attia, Shaimaa Naser, Nihad Dib, and Raed M. Shubair. "Compact design of UWB CPW-fed-patch antenna using the superformula." In 2016 5th International Conference on Electronic Devices, Systems and Applications (ICEDSA), pp. 1-4. IEEE, 2016.
53. E. M. Al-Ardi, R. M. Shubair, and M. E. Al-Mualla. "Performance evaluation of the LMS adaptive beamforming algorithm used in smart antenna systems." In 2003 46th Midwest Symposium on Circuits and Systems, vol. 1, pp. 432-435. IEEE, 2003.
54. Hadeel Elayan, Cesare Stefanini, Raed M. Shubair, and Josep Miquel Jornet. "End-to-end noise model for intra-body terahertz nanoscale communication." IEEE transactions on nanobioscience 17, no. 4 (2018): 464-473.
55. Muhammad S. Khan, Adnan Iftikhar, Raed M. Shubair, Antonio D. Capobianco, Benjamin D. Braaten, and Dimitris E. Anagnostou. "A four element, planar, compact UWB MIMO antenna with WLAN band rejection capabilities." Microwave and Optical Technology Letters 62, no. 10 (2020): 3124-3131.
56. Satish R. Jondhale, Raed Shubair, Rekha P. Labade, Jaime Lloret, and Pramod R. Gunjal. "Application of supervised learning approach for target localization in wireless sensor network." In Handbook of Wireless Sensor Networks: Issues and Challenges in Current Scenario's, pp. 493-519. Springer, Cham, 2020.
57. Hadeel Elayan, Raed M. Shubair, Akram Alomainy, and Ke Yang. "In-vivo terahertz em channel characterization for nano-communications in wbans." In 2016 IEEE International Symposium on Antennas and Propagation (APSURSI), pp. 979-980. IEEE, 2016.
58. Ahmed A. Ibrahim, and Raed M. Shubair. "Reconfigurable band-notched UWB antenna for cognitive radio applications." In 2016 16th Mediterranean Microwave Symposium (MMS), pp. 1-4. IEEE, 2016.
59. Raed Shubair, and Rashid Nuaimi. "Displaced sensor array for improved signal detection under grazing incidence conditions." Progress in Electromagnetics Research 79 (2008): 427-441.

60. Hadeel Elayan, Raed M. Shubair, and Josep M. Jornet. "Bio-electromagnetic thz propagation modeling for in-vivo wireless nanosensor networks." In 2017 11th European Conference on Antennas and Propagation (EuCAP), pp. 426-430. IEEE, 2017.
61. Hari Shankar Singh, SachinKalraiya, Manoj Kumar Meshram, and Raed M. Shubair. "Metamaterial inspired CPW-fed compact antenna for ultrawide band applications." International Journal of RF and Microwave Computer-Aided Engineering 29, no. 8 (2019): e21768.
62. Raed M. Shubair, Abdulrahman S. Goian, Mohamed I. AlHajri, and Ahmed R. Kulaib. "A new technique for UCA-based DOA estimation of coherent signals." In 2016 16th Mediterranean Microwave Symposium (MMS), pp. 1-3. IEEE, 2016.
63. Hadeel Elayan, and Raed M. Shubair. "On channel characterization in human body communication for medical monitoring systems." In 2016 17th International Symposium on Antenna Technology and Applied Electromagnetics (ANTEM), pp. 1-2. IEEE, 2016.
64. Omar Masood Khan, Qamar Ul Islam, Raed M. Shubair, and Asimina Kiourti. "Novel multiband Flamenco fractal antenna for wearable WBAN off-body communication applications." In 2018 International Applied Computational Electromagnetics Society Symposium (ACES), pp. 1-2. IEEE, 2018.
65. M. I. AlHajri, R. M. Shubair, L. Weruaga, A. R. Kulaib, A. Goian, M. Darweesh, and R. AlMemari. "Hybrid method for enhanced detection of coherent signals using circular antenna arrays." In 2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, pp. 1810-1811. IEEE, 2015.
66. Hadeel Elayan, Raed M. Shubair, and Nawaf Almoosa. "In vivo communication in wireless body area networks." In Information Innovation Technology in Smart Cities, pp. 273-287. Springer, Singapore, 2018.
67. Raed M. Shubair, Amer Salah, and Alaa K. Abbas. "Novel implantable miniaturized circular microstrip antenna for biomedical telemetry." In 2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, pp. 947-948. IEEE, 2015.
68. WafaNjima, Marwa Chafii, ArseniaChorti, Raed M. Shubair, and H. Vincent Poor. "Indoor localization using data augmentation via selective generative adversarial networks." IEEE Access 9 (2021): 98337-98347.
69. Hadeel Elayan, Raed M. Shubair, and Josep M. Jornet. "Characterising THz propagation and intrabody thermal absorption in iWNSNs." IET Microwaves, Antennas & Propagation 12, no. 4 (2018): 525-532.
70. Sandip Ghosal, Arijit De, Ajay Chakrabarty, and Raed M. Shubair. "Characteristic mode analysis of slot loading in microstrip patch antenna." In 2018 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, pp. 1523-1524. IEEE, 2018.
71. Raed M. Shubair. "Improved smart antenna design using displaced sensor array configuration." Applied Computational Electromagnetics Society Journal 22, no. 1 (2007): 83.
72. Dana Bazazeh, Raed M. Shubair, and Wasim Q. Malik. "Biomarker discovery and validation for Parkinson's Disease: A machine learning approach." In 2016 International Conference on Bio-engineering for Smart Technologies (BioSMART), pp. 1-6. IEEE, 2016.
73. Yazan Al-Alem, Ahmed A. Kishk, and Raed M. Shubair. "Enhanced wireless interchip communication performance using symmetrical layers and soft/hard surface concepts." IEEE Transactions on Microwave Theory and Techniques 68, no. 1 (2019): 39-50.
74. R. M. Shubair, and A. Merri. "A convergence study of adaptive beamforming algorithms used in smart antenna systems." In 11th International Symposium on Antenna Technology and Applied Electromagnetics [ANTEM 2005], pp. 1-5. IEEE, 2005.
75. Mayar Lotfy, Raed M. Shubair, Nassir Navab, and Shadi Albarqouni. "Investigation of focal loss in deep learning models for femur fractures classification." In 2019 International Conference on Electrical and Computing Technologies and Applications (ICECTA), pp. 1-4. IEEE, 2019.
76. Yazan Al-Alem, Ahmed A. Kishk, and Raed M. Shubair. "One-to-two wireless interchip communication link." IEEE Antennas and Wireless Propagation Letters 18, no. 11 (2019): 2375-2378.
77. E. M. Ardi, R. M. Shubair, and M. E. Mualla. "Adaptive beamforming arrays for smart antenna systems: A comprehensive performance study." In IEEE Antennas and Propagation Society Symposium, 2004., vol. 3, pp. 2651-2654. IEEE, 2004.
78. S. Elmeadawy, and R. M. Shubair. "Enabling technologies for 6G future wireless communications: Opportunities and challenges. arXiv 2020." arXiv preprint arXiv:2002.06068.
79. Yazan Al-Alem, Raed M. Shubair, and Ahmed Kishk. "Efficient on-chip antenna design based on symmetrical layers for multipath interference cancellation." In 2016 16th Mediterranean Microwave Symposium (MMS), pp. 1-3. IEEE, 2016.
80. Mohamed Ibrahim Alhajri, N. T. Ali, and R. M. Shubair. "2.4 ghz indoor channel measurements." IEEE Dataport (2018).
81. Hadeel Elayan, Cesare Stefanini, Raed M. Shubair, and Josep M. Jornet. "Stochastic noise model for intra-body terahertz nanoscale communication." In Proceedings of the 5th ACM International Conference on Nanoscale Computing and Communication, pp. 1-6. 2018.

82. Nadeen R. Rishani, Raed M. Shubair, and GhadahAldabbagh. "On the design of wearable and epidermal antennas for emerging medical applications." In 2017 Sensors Networks Smart and Emerging Technologies (SENSET), pp. 1-4. IEEE, 2017.
83. Raed M. Shubair, and Hadeel Elayan. "Enhanced WSN localization of moving nodes using a robust hybrid TDOA-PF approach." In 2015 11th International Conference on Innovations in Information Technology (IIT), pp. 122-127. IEEE, 2015.
84. Hadeel Elayan, Hadeel, and Raed M. Shubair. "Towards an Intelligent Deployment of Wireless Sensor Networks." In Information Innovation Technology in Smart Cities, pp. 235-250. Springer, Singapore, 2018.
85. Asimina Kiourti, and Raed M. Shubair. "Implantable and ingestible sensors for wireless physiological monitoring: a review." In 2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, pp. 1677-1678. IEEE, 2017.
86. M. I. AlHajri, N. T. Ali, and R. M. Shubair. "2.4 ghz indoor channel measurements data set." UCI Machine Learning Repository (2018).
87. Abdul Karim Gizzini, Marwa Chafii, Ahmad Nimr, Raed M. Shubair, and Gerhard Fettweis. "Cnn aided weighted interpolation for channel estimation in vehicular communications." IEEE Transactions on Vehicular Technology 70, no. 12 (2021): 12796-12811.
88. Yazan Al-Alem, Raed M. Shubair, and Ahmed Kishk. "Clock jitter correction circuit for high speed clock signals using delay units a nd time selection window." In 2016 16th Mediterranean Microwave Symposium (MMS), pp. 1-3. IEEE, 2016.
89. M. I. AlHajri, N. T. Ali, and R. M. Shubair. "2.4 ghz indoor channel measurements data set." UCI Machine Learning Repository, 2018."
90. Nishtha Chopra, Mike Phipott, Akram Alomainy, Qammer H. Abbasi, Khalid Qaraqe, and Raed M. Shubair. "THz time domain characterization of human skin tissue for nano-electromagnetic communication." In 2016 16th Mediterranean Microwave Symposium (MMS), pp. 1-3. IEEE, 2016.
91. Melissa Eugenia Diago-Mosquera, Alejandro Aragón-Zavala, Fidel Alejandro Rodríguez-Corbo, Mikel Celaya-Echarri, Raed M. Shubair, and Leyre Azpilicueta. "Tuning Selection Impact on Kriging-Aided In-Building Path Loss Modeling." IEEE Antennas and Wireless Propagation Letters 21, no. 1 (2021): 84-88.
92. WafaNjima, Marwa Chafii, and Raed M. Shubair. "Gan based data augmentation for indoor localization using labeled and unlabeled data." In 2021 International Balkan Conference on Communications and Networking (BalkanCom), pp. 36-39. IEEE, 2021.
93. Hadeel Elayan, Raed M. Shubair, Josep M. Jornet, Asimina Kiourti, and Raj Mittra. "Graphene-Based Spiral Nanoantenna for Intrabody Communication at Terahertz." In 2018 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, pp. 799-800. IEEE, 2018.
94. Mikel Celaya-Echarri, Leyre Azpilicueta, Fidel Alejandro Rodríguez-Corbo, Peio Lopez-Iturri, Victoria Ramos, Mohammad Alibakhshikenari, Raed M. Shubair, and Francisco Falcone. "Towards Environmental RF-EMF Assessment of mmWave High-Node Density Complex Heterogeneous Environments." Sensors 21, no. 24 (2021): 8419.
95. Mohamed I. AlHajri, Nazar T. Ali, and Raed M. Shubair. "A cascaded machine learning approach for indoor classification and localization using adaptive feature selection." AI for Emerging Verticals: Human-robot computing, sensing and networking (2020): 205.
96. Abdul Karim Gizzini, Marwa Chafii, Shahab Ehsanfar, and Raed M. Shubair. "Temporal Averaging LSTM-based Channel Estimation Scheme for IEEE 802.11 p Standard." arXiv preprint arXiv:2106.04829 (2021).
97. Yazan Al-Alem, Ahmed A. Kishk, and Raed Shubair. "Wireless chip to chip communication link budget enhancement using hard/soft surfaces." In 2018 IEEE Global Conference on Signal and Information Processing (GlobalSIP), pp. 1013-1014. IEEE, 2018.
98. Mohamed I. AlHajri, Raed M. Shubair, and Marwa Chafii. "Indoor Localization Under Limited Measurements: A Cross-Environment Joint Semi-Supervised and Transfer Learning Approach." In 2021 IEEE 22nd International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), pp. 266-270. IEEE, 2021.
99. Abdul Karim Gizzini, Marwa Chafii, Shahab Ehsanfar, and Raed M. Shubair. "Temporal Averaging LSTM-based Channel Estimation Scheme for IEEE 802.11 p Standard." arXiv preprint arXiv:2106.04829 (2021).
100. Yazan Al-Alem, Yazan, Ahmed A. Kishk, and Raed M. Shubair. "Employing EBG in Wireless Inter-chip Communication Links: Design and Performance." In 2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting, pp. 1303-1304. IEEE, 2020.
101. W. Tang et al., "Wireless Communications With Reconfigurable Intelligent Surface: Path Loss Modeling and Experimental Measurement," in IEEE Transactions on Wireless Communications, vol. 20, no. 1, pp. 421-439, Jan. 2021.
102. M. Mozaffari, W. Saad, M. Bennis and M. Debbah, "Optimal Transport Theory for Cell Association in UAV-Enabled Cellular Networks," in IEEE Communications Letters, vol. 21, no. 9, pp. 2053-2056, Sept. 2017.