Response to the comments of reviewer #1:

We thank the reviewer for the valuable comments and the time to carefully examine the manuscript. In the following the comments of the reviewer are in black and our responses are in blue.

General assessment.

The paper underpins the potential of rainfall estimation employing commercial microwave links (CMLs) from cellular telecommunication networks by using a full-year of data over entire Germany. The size of the dataset in terms of its coverage and number of CMLs is unprecedented. The original 1-minute temporal resolution is very high compared to other studies, which typically have 15-minute sampling strategies. Good results are obtained against a high-quality gauge-adjusted radar rainfall dataset, except for non-liquid precipitation, which was to be expected. Different rain event detection and wet antenna attenuation correction algorithms are compared. The evaluation of CML-based path-averaged rainfall rates or sums and CML rainfall maps is fairly extensive. The paper is well written and clearly contributes to the upscaling of CMLs for rainfall monitoring. I congratulate the authors on obtaining such a large dataset, and the work they have done to facilitate this (Chwala et al., 2016).

Despite this positive assessment, I do have a number of more serious comments:

1) A comparison of the quality of CML-based rainfall estimates with those from other studies is completely missing. Please have a look at e.g. de Vos et al. (2019), who provide an overview for studies based on Dutch CML data, having a similar climate as many regions in Germany (see Table A1). Naturally, a fair comparison is only possible in case of similar thresholds and metrics, which may complicate some comparisons. It seems that no threshold is applied in your work, i.e. also zero rainfall estimates are incorporated. Please state this explicitly in your manuscript. You may also consider to show metrics for other thresholds, e.g. > 1mm. The performance can be highly dependent on the chosen threshold. This could facilitate the comparison with other studies. I miss the (relative) bias in the mean in e.g Figure 6 and Table 2.
Response: We agree with the reviewer that a comparison with other studies would add value to this study. We also agree that a fair comparison requires similar thresholds. Differences in the CML-network density and potential differences of reference datasets do not allow a purely quantitative comparison of the actual values, though. Nevertheless we see the benefit of making our results comparable with results of other studies.
We appreciate the comprehensive overview of CML-rainfall studies in the Netherlands given in de Vos et al. (2019) and will base our selection of comparisons on their Table A1.
Regarding the threshold, we can state that we applied a threshold of >= 0.1 mm/h for specific metrics, but did not made the use of this threshold clear enough throughout manuscript. The threshold only impacts the results of the performance metrics which are based on the differentiation between ‘wet’ and ’dry’ periods. Also, for the density scatter plots we do not show pairs where both CML derived rain rates and the reference are dry. We will explain and highlight the use and implications of the threshold in the *Methods* and *Result* section.
Of course, the selection of another threshold can have an impact on the metrics, as low rain intensities are typically more frequent, but harder to detect with CMLs.

We suggest to make the following additions to our current analysis:

1. We will apply different thresholds: 0 mm, >= 0.1 mm and >= 1.0 mm for calculating the performance metrics of the path-averaged CML rain rates and discuss the results
2. We will discuss our results of path-averaged rain rates in comparison to the performances achieved in the respective studies from the Netherlands
3. As suggested by the reviewer, we will add the (relative) bias in the appropriate places e.g. Figure 6 and Table 2.

2) It would be interesting to see scatter density plots or metrics of daily path-averaged rainfall (e.g. as. Fig. 6). It would also be interesting to see scatter density plots or metrics of hourly and daily interpolated rainfall. This would also help to compare results with those from other studies.
Response: We agree that both suggestions are valuable for an increased comparability with other studies.

We suggest to make the following additions to our current analysis:

1. We will expand Fig. 6 to a 2x4 matrix, which will show hourly and daily path averaged scatter-density plots for each season and include metrics accordingly.
2. We will add a similar 2x4 matrix figure to the section *4.4 Rainfall Maps* which will present hourly and daily scatter-density plots derived from interpolated rainfall maps for each season and include metrics accordingly. For this figure and the calculation of the metrics we will use 'reference >= 0.1' mm as threshold as it is used in Overeem et al. (2016) and Rios Gaona et al. (2017).

Specific comments.
1. pp. 1., l. 14-16: This is quite a bold statement. Though results are definitely good, correlation is not perfect and especially the coefficient of variation is rather high (Table2). Although, part of this can be explained by representativeness errors, I think the statement is a bit too strong.
Response: We agree with the reviewer and will weaken the statement to the expression "good agreement".

2. pp.2, l. 14-18: Add some information on geostationary satellite products. These have typically a fairly high temporal resolution of 15 min, but provide rather indirect and therefore less accurate rainfall estimates. In addition, you could state that satellite products often have a limited spatial resolution, e.g. 0.1 degrees for GPM IMERG.
Response: We will extend the section about satellite products and will elaborate more on the spatial and temporal constraints and the differences between geostationary satellites and satellites in Low Earth orbits.

3. pp. 3., l. 21-22: Mention that all these gauges report hourly rainfall and add their spatial density (at least for the German ones), e.g. number of gauges per square kilometer.
Response: We will add more information on the rain gauges used to adjust the radar product which are automatic rain gauges of the German Weather Service with an hourly resolution and a spatial density of 0.003 gauges per square kilometer or one gauge per 325 square kilometers.

4. pp. 3: Some more details on the reference dataset could be mentioned. What kind of rain gauge adjustment was performed (bias, spatial and what name)? Were dual-pol based algorithms employed, e.g. for clutter removal, attenuation correction, Kdp-Ror Zdr-Zh-R rainfall retrieval? Why did you choose this radar rainfall product (perhaps:this is the shortest duration for which the radar product has been adjusted with gauges;even better radar products exist using more gauge data, but we wanted to show the performance with respect to a (near) real-time radar product). Is the used RADOLAN product really available in real time or is there a slight latency?
Response: We think we provided the necessary information on the reference data set as well as the literature providing further information. But we can add a very brief statement on the technology behind RADOLAN-RW (real-time, hourly, approx 15 minute delay, single-pol national radar composite adjusted with a mixture of additive and multiplicative rain gauge adjustment). Furthermore we will extend the explanation on why we use this product and relate this explanation to the properties of the RADOLAN-RW.

5. pp. 4, l. 5: Is this Ericsson network sufficient to provide full coverage over Germany, or is this one of the CML types used in the network of this company?
Response: Indeed, we currently only have access to the CML network of one cellular provider and only to one CML type, the Ericsson MINI-LINK Traffic Node system. Therefore, we have limited spatial

coverage in some regions of Germany, especially the north eastern part. Although, a 20 km buffer around the CMLs does not provide complete spatial coverage (in the north eastern part, as shown in Fig. 8), we have a high coverage over the rest of Germany.

6. pp. 4, l. 11: How do you select the sub-link when two are available? Are there any criteria involved?
Response: We always use the first listed sub-link of a given CML. We will add this information to the manuscript.

7. pp. 4, l. 19-23: Is the availability of radar data 100%? Please mention the availability. Is this availability taken into account, e.g. when comparing the radar-based versus CML-based rainfall maps?
Response: Yes, the availability of the processed reference, RADOLAN-RW along CML path, is 100%. When comparing path-integrated rainfall we exclude the pairs where CML derived rainfall is missing. For the quantitative comparison of radar and CML-based rainfall maps, which we will introduce in the revised version, we will use a coverage map that depends on CML data availability. This assures that we only validate parts of the grid which is within our defined coverage region, maximum 30km from a CML.

8. pp. 6, l. 11: The authors could also add a reference to the overview paper by Messer et al. (2015).
Response: We will add the reference by Messer et al. (2015).

9. pp. 6, l. 14: "requires repeatedly testing with the complete data set": Does this imply that part of the methodology has been optimized using the complete data set, i.e. that the evaluation is not entirely independent?
Response: We did not optimize individual steps of the method, except for the optimized threshold for May 2018 with the use of the MCC (p. 8, l. 24 ff.). During the development of the CML processing we did, however, also invent approaches that did not work well, when applied to the whole data set. Finding out that a new idea is a dead end, is sped up significantly with the parallelized workflow. We will rephrase the sentence to make this clearer.

10. pp. 7: l. 8-11 & p.8, l. 1-2: Are these checks performed for each month? So that a link may be discarded for one month, but be available for another month?
Response: These checks were performed for each month individually, yes. We will make this fact more clear in the manuscript.

11. pp. 8, l. 23: Can you provide a reference for the 5 percent of the time it is raining? Here you assume that it is equally distributed over Germany.
Response: We took the 5 percent from Schleiß and Berne (2010) who introduced the rolling standard deviation method. For the analyzed period of one year this value is more or less arbitrary because its reasoning is based on rainfall climatology. Of course, we are aware that this climatological threshold does not pay justice to the spatial and temporal variability of rainfall, but rather is a robust approach and simple way to provide a first rain event detection. In our study, this climatological approach, which was suggested by the inventors of the method we use, serves as a reference method to show the improvement by the q80 method.

12. pp. 8, l. 23-25: Could sources of error also constitute part of this 5 percent? So, assuming that 5 percent of the time it is indeed raining, this percentage would be too low if sources of error resulting in attenuation during dry periods have a similar magnitude.
Response: Yes, this is possible and is yet another drawback of the climatological (5-percent) method. Our proposed q80-method should be a lot more robust against these errors because it takes the general noisiness of the TRSL as basis for setting the threshold. Still, this method is not free from errors in the form of misclassifications. But as can be seen in Figure 4, there is a clear improvement over the climatological method.

13. pp. 8, l. 26-29 & pp. 9, l. 4-6: Can you provide somewhat more information on the optimization (e.g. which criteria)?
Response: Of course, we will include this information in the respective parts of the manuscript. We will explain this in more detail by adding a text similar to e.g. "The optimal thresholds (pp. 7, l. 26ff.) are obtained in the following way: We process each individual CML in May 2018 with a range of possible thresholds for the rolling standard deviation method and calculate the binary measure MCC. We pick the threshold with the highest MCC for each individual CML and use it over the whole analysis period."

14. pp. 8, l. 33: Replace "for of" by "for".
Response: We will correct this typo.

15. pp. 9, l. 19: And what determines the decrease after an event?
Response: Schleiss and Berne (2013) found an exponential decrease after rain events in their data. But their WAA scheme does not explicitly model this decay since, as they write, "it is already contained in the values
of a_i" (a_i is their total path attenuation after removal of the baseline). Hence, the WAA scheme with its exponential increase is only applied when the rain event detection considers the time step as wet, i.e. during a detected rain event.

16. pp. 9, l. 25: Do all these Ericsson antennas have the same cover?
Response: Based on the antennas that are used on Ericsson MINI-LINK Traffic Node CMLs that we have already had in our lab, we can say that there are at least two different types of covers. We took the value of 4.7 mm thickness from an 18 GHz antenna cover made from polycarbonate.

17. pp. 9, l. 24: Is this 2.3 dB for one or two antennas? Is this value reasonable compared to the literature? In the wet antenna experiment from Van Leth et al. (2018) a value of 3-5 dB for one antenna was found (although this was not real rainfall).
Response: 2.3 dB is the maximal WAA for the whole system, i.e. for both antennas. We took the value from Schleiss et al. (2013) who also used a CML for their study. Overeem et al. (2016) and the related studies with the Dutch CML data use a similar value. We, however, cannot say whether or not the real WAA does reach higher values at the CMLs in our data set. But we also do not know if both, one or none of the two antennas get wet during an individual rain event. Generally speaking, there is certainly room for improving WAA estimation methods. But in this study we want to apply a simple technique based on existing methods. We will explain our reasoning to choose the 2.3 dB better in the revised manuscript.

18. pp. 10, l. 5: Replace "the on" by "on".
Response: We will correct this typo.

19. pp. 11, l. 18: Replace "also is" by "also".
Response: We will correct this typo.

20. pp. 13, l. 8 & pp. 18, l. 1: I expect that especially melting snow and ice on the covers gives rise to attenuation.
Response: Indeed, we will add melting snow and ice on the covers to the causes of additional attenuation.

21. pp. 13, l. 20: I suppose that the reference is used to select rain rates above 5mm/h?
Response: Yes, the reference is used for selecting rain rates above 5mm/h. We will make this more clear in the revised manuscript.

22. pp. 14 & 15: For clarity I suggest to add that these are path-averages (i.e. not based on maps).
Response: We will add this in the caption of the figures.

23: pp. 14, l. 14: You could add that e.g. in the southwestern part of Germany this is the case.
Response: We will add this more precise description to the revised manuscript.

24. pp. 15, l. 7: You could add that an advantage of the applied interpolation method is its robustness and speed.
Response: We will add both advantages of IDW interpolation technique to the revised manuscript.

25. pp. 18.: You could recommend that studying the quality of rainfall maps for shorter durations, e.g. 1 minute, would be an interesting follow-up study, especially for urban water management.
Response: We will add this to the list of possible future possibilities of this methods and the presented data set.

26. Figures 8 & 9: The tick marks do often not match the transition from one color scale to another.
Response: We will place the tick marks on the correct position.

27. pp. 16, l. 14-15: I think that algorithms using neighbouring CMLs are much more promising than satellite-based ones provided that the density of the CML network is high enough.
Response: We agree that in dense CML networks these algorithms work well and will add this to the revised manuscript.

28. pp. 17: You could add as a recommendation to compare methods from different research groups on the same dataset, e.g. concerning rain event detection and wet antenna attenuation correction.
Response: Such a work would be an important step in making the work of different research groups really comparable. We will add this to the *Conclusion*.

29. pp. 17, Figure 9: You could consider adding a map showing the relative or absolute difference of CML-based rainfall with respect to RADOLAN.
Response: As we treat each CML only as a single point in the interpolation, a map showing the differences of CML and radar-based rainfall will show differences for almost all parts of the analyzed region. Also, since radar is a spatial sensor, the spatial variability in the radar reference is a lot higher than that of the interpolated CML rainfall fields, resulting in noisy difference plots. We will include scatter density plots of CML vs. radar-based rainfall maps as described in the response to the general comment 2), which will serve as basis of the comparison of both maps.

30. pp. 17. Are there any plans of merging CML data with RADOLAN? That could be an interesting recommendation. And what do you expect in terms of improved performance and especially for which areas (cities, valleys, ...)?
Response: Yes, at the moment we investigate merging CML data into the RADOLAN-process in a BMBF funded project called HoWa-innovativ (https://www.howa-innovativ.sachsen.de). As the reviewer guessed correctly, we expect the largest improvements in cities and valleys, where radar observations are hampered by ground clutter, beam-blockage or the vertical profile of reflectivity. We will add the potential of merging CML and radar data to the *Conclusion*.

References.

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