A METHOD TO COUNT BACKCOUNTRY SKIERS FROM BLUETOOTH LOW ENERGY SIGNALS

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Quantifying the number of people participating in backcountry skiing is essential for understanding patterns of use, user characteristics, and exposure to avalanche hazard. However, monitoring backcountry use remains challenging due to the dispersed, unregulated, and remote nature of these areas. Existing approaches often rely on surveys, manual observations, or indirect methods, each with limitations in spatial coverage, scalability, and cost. This study presents the development and evaluation of a scalable method for quantifying backcountry use based on Bluetooth Low Energy (BLE) sensing. The method builds on a multi-year development process, progressing from proof-of-concept to large-scale deployment. Initial testing in the Tromsø region during 2022–2023 confirmed that the prototype worked by comparing its counts with the number of people observed using a time-lapse photography. Subsequent deployments included 30 devices (2023–2024), where a firmware issue reduced the operational period, followed by smaller-scale validation deployments in Sogndal (2024–2025). The most recent phase (2025–2026) includes 50 devices deployed in Lyngen and 8 in Sogndal. The sensing approach is based on detecting nearby BLE devices as a proxy for human presence. A key challenge in BLE-based counting is the potential for repeated detections of the same individual and variation in device detectability. To address this, the method is validated using time-lapse photography to identify the number of backcountry skiers, enabling calibration of detection ratios and uncertainty estimates. The results show that BLE sensing provides a cost-effective, scalable, and flexible method for monitoring backcountry use in remote areas, with strong potential to improve estimates of exposure in avalanche terrain and support more effective avalanche warning services.

KEYWORDS: Counting, Backcountry skiing, BLE

1. INTRODUCTION

Understanding how many people participate in backcountry skiing is fundamental for assessing avalanche risk, evaluating trends in fatalities, and improving avalanche warning services. Fatality counts alone provide an incomplete picture of risk because they lack the denominator: the number of people exposed to avalanche terrain. Without reliable estimates of backcountry use, it is difficult to determine whether changes in avalanche accidents reflect changes in risk, participation, or both (Jamieson et al., 2009; Münter, 2003). Furthermore, avalanche forecasting services remain largely blind to the size, spatial distribution, and temporal patterns of their user group, limiting opportunities to evaluate and improve forecast products.

Quantifying backcountry use is inherently challenging because recreation occurs across large, remote, and unregulated mountain landscapes without predefined trails or mandatory access points. Skiers may start from different trailheads and spread out over large areas. Consequently, conventional counting methods, such as infrared counters, induction loops, or manual observations, are difficult to implement at regional scales. Previous studies have relied on national surveys (Lamprecht & Stamm, 2000; Lamprecht et al., 2008, 2014; Bürgi et al., 2021), direct observations (Zweifel et al., 2006; Saly et al., 2020), social media (Techel et al., 2015), surveys (Sole, 2008; Procter et al., 2014), and indirect methods such as mobile phone network data and beacon counters (Toft et al., 2023; Toft et al., 2025). Each approach involves trade-offs in spatial coverage, scalability, cost, or accuracy, and no single method has proven suitable for continuous monitoring of backcountry recreation over large regions (Langford et al., 2020).

Bluetooth Low Energy (BLE) sensing offers a promising alternative. By detecting BLE signals emitted from smartphones, smartwatches, headphones, and other personal devices, it is possible to estimate human presence without requiring users to install dedicated applications or carry specialized equipment. Although BLE sensing has become widely used for pedestrian counting and mobility monitoring in urban environments, its application to remote mountain recreation has, to our knowledge, not previously been investigated.

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2. BACKGROUND

2.1 Bluetooth Low Energy

Bluetooth Low Energy (BLE) is a short-range wireless communication protocol designed for devices requiring very low power consumption. Modern consumer electronics, including smartphones, smartwatches, wireless headphones, fitness trackers, and many avalanche airbags, periodically broadcast BLE advertisement packets that can be detected without pairing. This makes BLE a promising proxy for human presence while allowing sensors to operate for multiple years on a single battery.

Compared with conventional trail counters, BLE sensing offers several advantages for monitoring backcountry skiing. Unlike conventional trail counters, BLE sensors do not require users to pass through a narrow trail corridor and can therefore be deployed independently of established trails and other natural bottlenecks. A regular BLE antenna has detection ranges of up to approximately 100 m, require no user interaction, and can continuously monitor the detection area with very low power requirements. However, BLE sensing also introduces challenges. Individuals may carry multiple BLE-enabled devices, while others may carry none. Consequently, the number of detected BLE devices is not directly equivalent to the number of people and requires calibration using an independent reference method.

3. DEVELOPMENT

3.1 Phase I: Can it work?

The first phase focused on demonstrating that BLE signals could be used to detect backcountry skiers in a remote mountain environment. A prototype was constructed using an Arduino Nano 33 BLE microcontroller connected to a 12 V LiPo battery housed in a waterproof Peli case. The unit continuously scanned for nearby BLE advertisements and stored detections locally in the Arduino flash memory.

The prototype was deployed at a popular backcountry access point in the Tromsø region during the 2022–2023 winter season. Since no remote communication system had yet been implemented, the data was retrieved manually after a couple of weeks of deployment. Simultaneously, a time-lapse camera recorded all passing skiers, providing a reference dataset.

The time-lapse photos demonstrated that the prototype consistently detected BLE signals whenever people were present in the monitored area. Although the system was not yet suitable for operational deployment, the experiment confirmed that BLE sensing represented a viable approach for enumerating backcountry recreationists.

3.2 Phase II: Can it survive?

Following the successful deployment of the prototype, a second-generation BLE counter was developed for long-term field deployment. The system retained the Arduino Nano 33 BLE microcontroller while adding an LTE/IoT communication module and a 3.7 V, 14 Ah lithium battery, all housed within a weatherproof enclosure. This allowed data to be transmitted wirelessly, eliminating the need for manual data retrieval.

The firmware was optimized for ultra-low power consumption through duty-cycled scanning and sleep modes, resulting in an estimated battery life of ~1 year. The scanner was configured to detect BLE advertisements within approximately 50-100 m from the installation site. The material cost of each unit was approximately NOK 2500, while the total production cost, including assembly, testing, and deployment preparation, is estimated at NOK 4000–5000 per unit when manufactured at scale. This makes large-scale deployments economically feasible compared to e.g. beacon checkpoints which are 5-10 times as expensive (Toft et al. 2025).

During the 2023–2024 winter season, 30 BLE counters were deployed in northern Norway. Although a firmware issue reduced the operational period of all units to approximately 50 days. The issue was traced to incorrect handling of the Arduino's internal millisecond timer which rolls over after approximately 49.7 days of continuous operation. The timer overflow caused the BLE scanning and logging routine to stop, although the hardware itself remained operational. Despite this limitation, the deployment demonstrated that the hardware platform, remote communication, and low-power design were sufficiently robust for regional monitoring.

3.3 Phase III: Can it count accurately?

The third phase shifted the focus from technology development to quantitative validation. A dedicated validation study was conducted in Sogndal, Luster, and adjacent parts of Jotunheimen, using time-lapse cameras as the reference method for observed backcountry use. Because the BLE counters detect Bluetooth devices rather than individuals, a one-to-one relationship between BLE detections and camera-counted people was not expected. Validation therefore focused on whether temporal variation in BLE detections corresponded to variation in the number of people observed by the cameras.

The relationship between camera observations and BLE detections was assessed separately for each location using Pearson's correlation coefficient (r) with 95% confidence intervals. Pearson's r was selected as the primary measure because it quantifies the strength of the linear relationship independently of differences in scale between the two measurement methods. Spearman's rank correlation coefficient (ρ) was additionally calculated as a sensitivity analysis to assess whether the observed relationships were robust to non-normality and influential observations.

In winter 2025, the second-generation BLE counters were evaluated at five locations over a planned 56-day period. Adverse weather and technical issues reduced the final validation dataset to paired observations from four locations. Across these observations, 538 backcountry skiers were identified by the time-lapse cameras, and 985 BLE devices were detected, corresponding to an overall ratio of 1.83 BLE devices per camera-counted person.

The strength of the relationship varied between locations. Pearson correlations were very high at Rindabotn[1] ($r = 0.989$) and Leirdalen ($r = 0.9999$), although the latter was based on only three paired observations and should therefore be interpreted with caution. Geisdalen showed a strong positive relationship ($r = 0.804$), whereas Svartholten showed a considerably weaker relationship ($r = 0.393$). The broad confidence intervals at locations with few observations illustrate the uncertainty associated with the short validation periods.

In winter 2026, the third-generation BLE counters were validated at Rindabotn[2] and Dyrhaugsryggen. Across the two locations, 705 backcountry skiers were identified by the time-lapse cameras, and 3591 BLE devices were detected. This corresponded to 4.36 BLE devices per camera-counted person at Rindabotn and 6.63 at Dyrhaugsryggen. Despite these substantially higher BLE-to-person ratios, the relationship with camera-observed use was very strong at both locations, with Pearson correlations of $r = 0.950$ (95% CI: 0.878–0.980) at Rindabotn and $r = 0.913$ (95% CI: 0.790–0.965) at Dyrhaugsryggen. Spearman correlations of 0.932 and 0.798, respectively, supported the same general pattern.

The validation results therefore indicate that the BLE counters can reproduce temporal variation in backcountry use even when the absolute number of detected BLE devices differs substantially from the number of people observed. However, the BLE-to-person ratio varied markedly both between locations and between counter generations. Ratios for the second-generation counters ranged from 1.63 to 2.29 BLE devices per person, whereas ratios of 4.36 and 6.63 were observed for the third-generation counters in 2026. The causes of this difference require further investigation and may include changes in hardware or software, scan settings, signal-strength thresholds, site characteristics, or changes in the number and type of BLE-emitting devices carried by users.

Overall, the results suggest that the primary strength of the BLE counters is their ability to track relative changes in backcountry use rather than directly measure absolute visitor numbers. Where the local relationship between BLE detections and people is known, BLE counts may also be converted into estimates of visitor numbers. Future work should therefore focus on identifying the factors controlling the BLE-to-person ratio and determining how stable this relationship is across locations, seasons, and counter generations.

Table 1: Validation results for second- and third-generation BLE counters in Indre Sogn and Jotunheimen.

Location	No. of days	No. of people	No. of BLE units	Ratio	Pearson r	95 % KI	Spearman ρ
Rindabotn[1]	11	339	615	1.81	0.989	0.956–0.997	0.968
Leirdalen	3	94	153	1,63	0.99993	–	1.000
Geisdalen	7	88	178	2,02	0.804	0.130–0.970	0.885
Svartholten	5	17	39	2,29	0.393	−0.749–0.947	0.205
Rindabotn[2]	21	478	2085	4,36	0.950	0.878–0.980	0.932
Dyrhaugsryggen	20	227	1506	6,63	0.913	0.790–0.965	0.798

3.4 Phase IV: Can it scale?

The most recent phase represents the transition from pilot testing to operational-scale monitoring. During the 2026 winter season, 50 BLE counters were deployed throughout the Lyngen region, with an additional eight units installed in Sogndal. To support deployment at this scale, a third-generation BLE counter was developed in cooperation with a Polish technology company. The new unit is substantially more compact than the previous prototypes, weighs approximately 700 g, and is housed in an IP67-rated enclosure, making it suitable for winter deployment in exposed mountain environments.

The third-generation counter provides flexibility in how BLE signals are sampled. Three main parameters can be configured: scan duration (P1), the interval between consecutive measurement cycles (P2), and the minimum received signal strength (RSSI) required for a device to be counted (P3). P1 and P2 can be set between 1 and 864,000 s, while the RSSI threshold can be adjusted between −100 and 0 dBm. Within each active BLE scan, the device uses a 62.5 ms scan interval and a 31.25 ms scan window. Together, these settings allow the detection rate, effective range, power consumption, and temporal resolution to be adapted to different monitoring locations.

Low power consumption was a key requirement for scaling the system. With P1 set to 3 s and P2 to 10 s, testing in an office environment with a high density of Bluetooth devices indicated an average current consumption of approximately 1.3 mA, corresponding to around 11 Ah per year. Using two ER34615 batteries with a combined capacity of approximately 38 Ah gives an estimated battery life of roughly three years under these settings. Longer measurement intervals can further extend battery life, with settings of 6 s and 20 s estimated to provide up to approximately six years of operation. Actual battery life will, however, depend on factors including cellular coverage, data transmission frequency and ambient temperature.

4. CONCLUSION

This paper presents the development and evaluation of a BLE-based counting system designed specifically for year-round deployment in remote backcountry terrain. The system has been developed through a multi-year process, progressing from prototype testing to large-scale operational deployments. The results demonstrate that BLE sensing provides a scalable and cost-effective method for quantifying backcountry use, creating new opportunities to estimate exposure to avalanche hazard and to better understand temporal and spatial patterns of recreation in avalanche terrain.

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