

# A Comprehensive Review of Smart Home Technologies for Elderly Support

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**Abstract**—A rapidly aging world population, sometimes referred to as the gray tsunami, places extraordinary values of socioeconomic strains on conventional healthcare infrastructures and care-giver resources. Consequently, there is the need for a paradigm shift to aging in place, to enable older adults as well as persons with disabilities to live independently and in safety in their own homes. This research provides a comprehensive review of key developments in Smart Home technologies and the Internet of Things over the past decade, with the desire of allowing autonomous life for the elderly. It systematically defines physiological, cognitive and psycho-social challenges of aging and this identifies Assisted Living and Smart Home architectures as a key area for solutions to these vulnerabilities. Furthermore, several technological interventions, such as automated health assessments, contactless vital sign monitors and intelligent medicine dispensers, are by themselves able to address a wide range of declines with age, the review considers. While the shift from reactive clinical interventions to proactive ambient monitoring offers great potential for improving the quality of life, such widespread use of these systems is confronted with huge systemic and infrastructural obstacles. Findings highlight the important need for universal interoperability protocols, human-centered design methodologies and strong data privacy measures. Ultimately, an integration of innovations such as Edge computing and Generative Artificial Intelligence will be required in order to successfully implement intelligent, pervasive environments as a necessary pillar of modern geriatric care.

**Keywords**— Smart Home; Ambient Assisted Living; IoT; Aging; Elderly; AI

## I. INTRODUCTION

The global demographic landscape is presently undergoing one of the largest and most unprecedented changes, with an aging that is rapidly increasing[1]. Statistical projections indicate that the number of individuals aged sixty-five and older, which stood at approximately 702.9 million in the year 2019, is anticipated to surge by 120 percent, reaching nearly 1.55 billion by the year 2050 as Figure 1 reveals. Concurrently, the cohort of individuals aged above eighty years old is expected to double, rising from 53.9 million to 109.1 million within the same timeframe [2].

This huge demographic shift, also known as the gray tsunami, places tremendous socioeconomic strains on traditional healthcare systems and are driving up the need for long-term care facilities, special medical intervention and 24-hour care support by caregivers. The sheer volume of aging people threatens to outstrip the supply of human caregivers, and will require a radical rethinking of the way geriatric care is delivered.

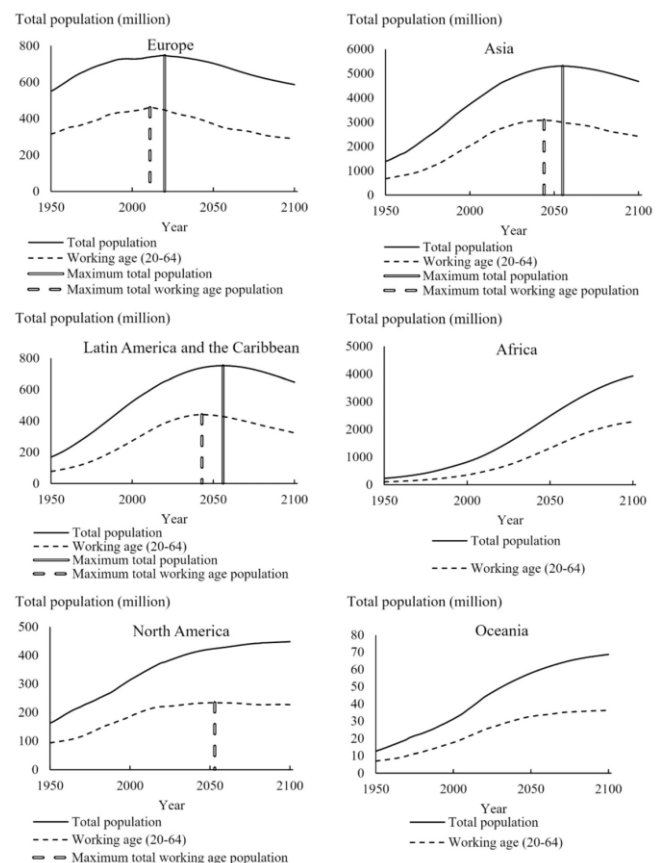


Fig. 1. Total and working age Population projections from year 1950 to 2100 [2]

To alleviate the immense burden on public health infrastructure and informal caregivers, a critical paradigm shift toward the concept of aging in place is evident [3]. Aging in place refers to the ability of older adults to live independently, safely, and comfortably in their own homes for as long as possible, delaying or

entirely avoiding the need for institutionalization. This transition is heavily reliant on the proliferation of the Internet of Things and the conceptualization of Ambient Assisted Living systems. Smart Homes enabled with pervasive computing, sophisticated sensor networks and artificial intelligence offer a continuous, non-obtrusive and holistic approach to healthcare monitoring [4]. By combining physical environments with digital health interventions, Smart Home technologies promise to reduce the risks posed by age-related physical and cognitive decline and turns conventional home into proactive healthcare ecosystems. Some of the ambient Assisted Living key factors are as shown in Figure 2 below:

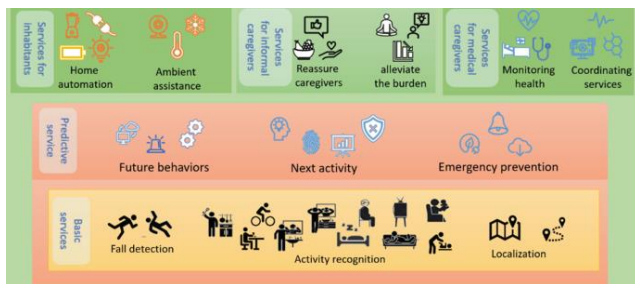


Fig. 2. Assisted Living factors that are important for the elderly [4]

This comprehensive review discusses the multidimensional architecture of Smart Home technologies that are especially for older adults looking at the physiological and cognitive pathologies that require technological intervention. This work is also for evaluating the underlying network protocols and hardware infrastructure required for the smooth functioning and provides an in-depth feature comparative analysis of the leading Smart Home prototypes and commercial systems. Furthermore, ethical, privacy, and adoption issues that healthcare encounters with the deployment of intelligent pervasive environments are discussed in this review, along with information on the course of artificial intelligence-enabled geriatric care in the future.

The manuscript is divided into 5 main thematic parts. The Introduction sets the context of the rapidly ageing world population and outlines the wide-ranging scope of the review. The second section examines the pathophysiology of aging in some of the bio-somatic, cognitive, and psychosocial conditions that require targeted technological intervention. In the third part, the architectural structure of Smart Homes is analyzed including an assessment of several different wired and wireless communication protocols. Following this, the review explains particular Ambient Assisted Living devices and elaborates an exhaustive comparative analysis of integrated Smart Home prototypes and the importance of artificial intelligence in processing data for automated health assessments. The following section discusses the ethical, privacy and infrastructural issues of deploying these pervasive environments. In the final part, the transformative potential of Smart Homes is concluded, including future trends towards Edge computing.

## II. THE PATHOPHYSIOLOGY OF AGING AND THE IMPERATIVE FOR TECHNOLOGICAL INTERVENTION

The biological process of aging is a complex, natural phenomenon, which is characterized by gradual deterioration of physiological functions, which reduce the ability of the body to regenerate cells and tissues [5]. Primary aging is the inevitable, time dependent decline that are associated even without the presence of the disease and include muscle loss, reduced bone density and a weakened immune system. At the cellular level this is caused by DNA damage, oxidative stress and the progressive shortening of telomeres (the protective caps at the end of the chromosomes). Secondary aging refers to alterations in the process of aging that are worsened by outside factors, environmental exposures and lifestyle factors, such as poor dieting or inactivity [6]. Together, these processes result in the build-up of vulnerabilities that ultimately leave older adults at risk for many chronic conditions and disabilities. Understanding these specific health challenges is an absolute requirement in order to target the design and implementation of Ambient Assisted Living technologies.

### A. Bio-Somatic and Chronic Diseases

Older people are highly prone to chronic bio-somatic diseases, which are diseases affecting the physical body and severely limit the activities of daily living [7]. In addition, having more than one chronic condition, happening simultaneously, increase the complexity of clinical management while exponentially increasing the need for continuous monitoring. Musculoskeletal disorders are an international common affair in the aging population.

Arthritis, a catch-all term meaning inflammation of a joint, highly limits one's ability to move and to control small motor movements [8]. The most common type, osteoarthritis, is caused by the gradual degradation of protective cartilage, most commonly in the weight bearing joints such as the knees and hips and the hands. The autoimmune disease of rheumatoid arthritis acts on the joints, in which the lining of the joints is attacked, causing the joints to become extremely swollen as well as causing systemic fatigue throughout the body [9]. Gout causes acute severe pain due to the crystallization of uric acid. Concurrently, osteoporosis results in a critical loss in bone mass and density such that bones become very porous and easily broken. There is a enormous risk of developing severe fractures from minor trauma, or falls, with this condition. In the case of a Smart Home however, such musculoskeletal limitations demand the use of voice activated environmental controls, automated door openers and assisting robotics that eliminate the need for fine motor dexterity or strenuous physical exertion [10].

Cardiovascular conditions and respiratory conditions are another large group of bio-somatic illness. Hypertension, the presence of chronically high blood pressure, is referred to as the silent killer because there is no symptom [11]. If it is not monitored, it results in serious cardiovascular events, such as heart attacks and strokes. A stroke is an

interruption of the blood supply to the brain due to either an Ischemic blockage or hemorrhage rupture of blood vessels to the brain causing sudden, profound deficits in motor and cognitive abilities. Respiratory ailments, such as chronic obstructive pulmonary disease, asthma and pulmonary fibrosis restrict the amount of air and oxygen flow causing chronic breathlessness and fatigue [12]. Diabetes mellitus, a form of metabolic disease caused by improper production or use of insulin, requires careful longitudinal observation of blood glucose levels to avoid the secondary sequelae of this disease, such as neuropathy and retinopathy. Smart Home technologies address this system diseases by constant and ambient telemetry based on wearable and smart environments to monitor vital signs, predict acute exacerbation of acute diseases and ensure strict medication compliance. The main scheme of diseases of elderly is at Figure 3 :

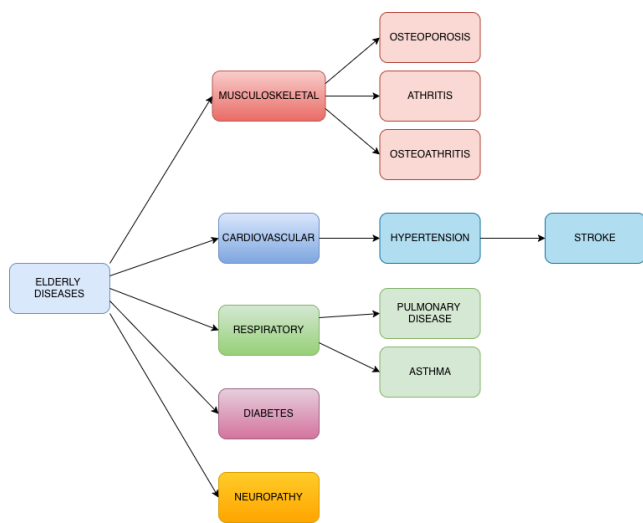


Fig. 3. Categorization of elderly diseases

Sensory impairments represent a critical compromise for the safety of an older adult to safely navigate through their environment [13]. Age-related macular degeneration results in the progressive deterioration of the central portion of the retina resulting in a loss of central vision necessary for reading or recognizing faces. Glaucoma, caused by a buildup of pressure inside the eyes, causes damage to the optic nerve and wears away at the edges of your peripheral vision. Hearing loss (presbycusis) is the gradual loss of the ability to interpret high-frequency sound as people grow older to the point they can't be heard by others and follow the conversation, which creates a profound social isolation [14]. In order to overcome these sensory deficits, intelligent environments would need to weave in multi-modal interfaces, such as haptic feedback mechanisms, adaptive high-contrast ambient lighting which automatically adjusts to the time of day and acoustic amplification loops that readily interface with hearing aids, shown in remarkable form at Figure 4 below [15].



Fig. 4. Automated systems implemented at Smart Homes for Elderly Support [15]

### B. Cognitive Decline and Neurodegenerative Disorders

Cognitive impairment, from mild memory impairment to very severe neurodegenerative disease that fundamentally changes an individual's reality and autonomy is exhibited at Figure 5. Such impairments relate to information processing, executive function, awareness in space and problem solving capabilities [16]. Alzheimer's disease is the most common cause of dementia, and is characterized by deposits of abnormal amyloid-beta plaques and tau tangles in the brain. This progressive disease starts with minimal memory loss and disorientation to eventually progress to a point where the person can't carry out basic self-care tasks or recognize loved ones. Parkinson's disease is a chronic neurological disease that results from the degeneration of dopamine-producing neurons [17]. It introduces severe motor symptoms such as resting tremors, muscular rigidity, slowness of movement and severe postural instability, which drastically increases the risk of falls. Parkinson's comes with other non-motor symptoms like sleep disturbances and cognitive changes. Because cognitive and neurodegenerative diseases critically affect an individual's ability to use complex interfaces or remember to wear tracking devices, Smart Homes must be based on passive, ambient monitoring. The deviations of the routine behaviours, such as wandering behaviours or gait velocity changes, are analysed by artificial intelligence algorithms to predict the onset or progression of these disorders without the need for active user input [18].

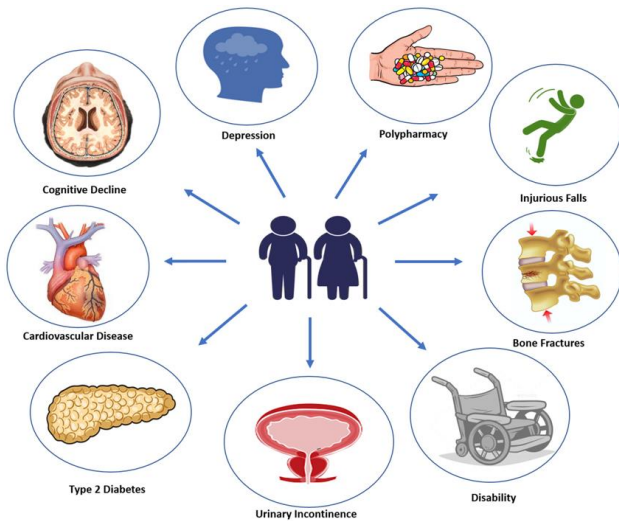


Fig. 5. Summarization of critical conditions and diseases related to aging [18]

The geriatric demographic also experiences unique psychosocial challenges that seriously affect their overall well-being. Older adults often suffer from mood disorders, such as major depressive and bipolar disorders which can manifest in an atypical fashion with somatic complaints and hypochondriacal ideation [19]. Anxiety disorders, fuelled by the fear of falling or losing independence, can contribute to extreme social withdrawal. Psychotic disorders, such as late-onset schizophrenia, involve severe distortions of internal and external reality, presenting as delusions or disorganized thought processes. Furthermore, personality disorders may persist or worsen in old age, complicating interpersonal relationships with caregivers. Social isolation is both a catalyst and a consequence of these mental health declines. Consequently, Smart Home technologies must transcend physical monitoring to include cognitive support and social engagement tools, providing virtual companionship, facilitating seamless remote communication with families, and monitoring behavioral biometrics, such as speech volume and socialization frequency, to detect early signs of clinical depression or isolation [20].

### III. THE ARCHITECTURE OF SMART HOME AND AMBIENT ASSISTED LIVING SYSTEMS

A Smart Home is a technologically augmented residence equipped with a network of sensors, actuators, and communication protocols that gather data, interact with the physical environment, and operate autonomously to enhance the occupant's comfort, security, and health [21]. The conceptual framework of the Smart Home is intrinsically linked to the Internet of Things, which refers to an ecosystem of physical objects embedded with technologies that enable them to sense, process, and exchange data over a network. When applied to geriatric care, this ecosystem forms the foundation of Ambient Assisted Living [22].

The architecture of a Smart Home system is generally stratified into multiple functional layers. The

perception layer consists of the physical hardware, including environmental sensors, wearable biomedical devices, and actuators as presented at Figure 5 [23-24].

The network or communication layer is the central nervous system that uses different types of wired and wireless protocols to send data from the perception layer to local gateways or cloud servers. The application and decision-making layer is the brain of the system; this layer is where data analytics and artificial intelligence algorithms are used to process the aggregated data and derive meaningful patterns in it, identify anomalies, and trigger appropriate responses or services [25]. This intelligent infrastructure can be used to monitor the environment in the home around the clock, without the need for intrusive monitoring, so the environment can adapt dynamically to the changing needs of the elderly occupants.

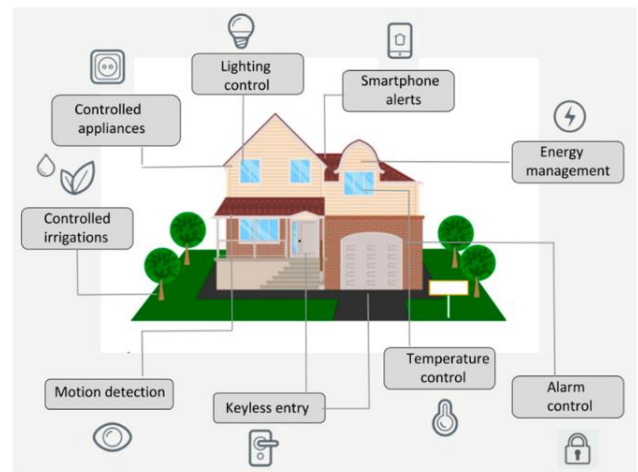


Fig. 6. Services provided at a Smart Home by utilizing smart sensing devices

The efficacy of a Smart Home relies entirely on the robustness, security, and efficiency of its communication protocols [24]. The heterogeneous nature of IoT devices requires a diverse array of networking standards, each optimized for specific constraints such as power consumption, data throughput, physical range, and existing infrastructure. These protocols are broadly categorized into wired and wireless technologies.

#### A. Wired Communication Protocols

Wired protocols utilize existing electrical infrastructure or dedicated data cables. They are highly reliable, immune to radio frequency interference, and capable of supporting high-bandwidth applications, making them highly suitable for permanent architectural retrofits in dedicated senior living facilities [26-29].

- BACnet, which stands for Building Automation and Control Networks, is a ubiquitous protocol designed specifically for the automation of large buildings. It is an open, vendor-neutral standard that ensures interoperability between diverse hardware and software systems. Operating across

various communication layers including Ethernet, IP, and RS-485, BACnet facilitates the seamless integration of Air Conditioning, lighting, access control, and energy management systems. Its scalability makes it ideal for large assisted living complexes where centralized facility management is required.

- Dupline is a decentralized system based on a two-wire bus network. It is designed for building automation and permits the transmission of both digital and analog signals over long distances. The decentralized design of Dupline makes the system more resilient; the devices that communicate over the bus share information directly, allowing them to make local decisions and reduces the system's dependence on a single central controller. This fault tolerance is extremely important in healthcare environments where the failure of a device could be a safety risk.
- Ethernet is the gold standard for high-speed, high bandwidth data transmission. Operating on the TCP/IP suite, Ethernet is a standardized mechanism for devices to communicate over local area networks using unique IP addresses. While it requires a lot of physical cabling, Ethernet ensures low latency and incredible reliability, making it the backbone of choice for central control hubs, gateway routers and high-definition video surveillance systems used for fall verification.
- KNX is an international open standard for home and building control. It uses a decentralised bus system, enabling devices from various manufactures to interoperate seamlessly. KNX supports multiple transmission media, including twisted pair wiring and radio frequency. Its robust intelligence is distributed across the network, optimizing energy efficiency by adjusting lighting and climate controls based on real-time occupancy and environmental sensors.
- X10 and Insteon are the next step in powerline communications. X10 is a legacy protocol that sends digital packets over existing electrical wiring, instead of requiring new cables. But X10 is limited by its slow transmission speeds, and is highly sensitive to electrical noise and interference. Insteon was created to address these shortcomings by using a dual mesh network architecture. Insteon transmits signals simultaneously on both the wireless radio frequencies and on the electrical powerline. This dual-path communication dramatically increases the network reliability, and by having a mesh topology, the devices can operate as communication repeaters thus increasing the operational range without delays due to the routing requirement through a central node. All wireless protocols used at Smart Home are illustrated at Figure 7.

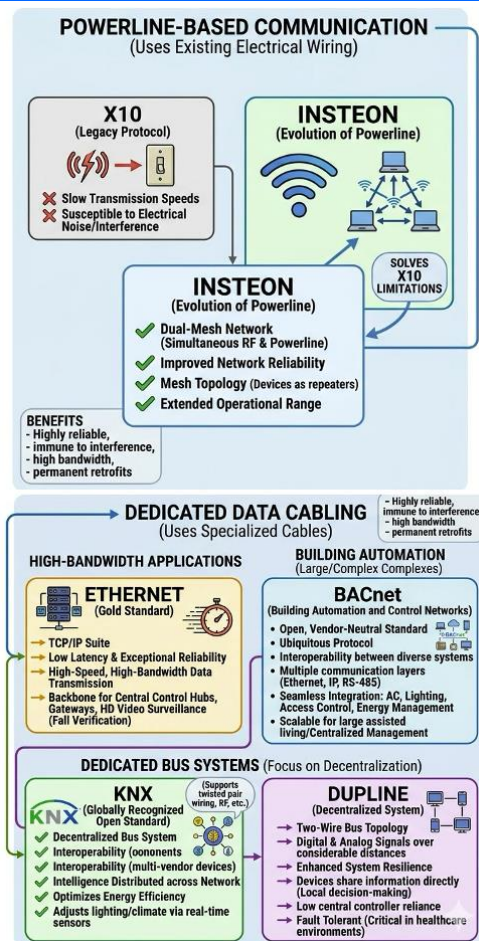


Fig. 7. Comparative overview of Smart Home wired protocols

### B. Wireless Communication Protocols

Wireless protocols are central to the operation of the Smart Home of the future, providing the ability to deploy sensors out of sight, as well as incorporating wearable health monitors. They are characterized with respect to their frequency bands, data rates, range, and power consumption characteristics [28-32]:

The 6LoWPAN protocol provides for transmission of IPv6 packets over low-power wireless personal area networks compliant with the IEEE 802.15.4 standard. It is responsible for providing IP connectivity for devices that are severely constrained in terms of resources, enabling microscopic sensors to talk directly to larger computer networks. It makes use of mesh networking, through means and communications routes are kept open even though primary links are susceptible to fail [28].

Bluetooth and its low power alternative called Bluetooth Low Energy -BLE are the leading preferences for short range device connectivity [29]. Operating in the 2.4 GHz frequency, Bluetooth supports point-to-point and mesh networking with a maximum distance of one hundred meters. Bluetooth Low Energy is explicitly geared towards the development of battery-powered IoT devices and wearables for health technology like smart watches and vital signs trackers. It enables devices to never

lose their connectivity and consume a fraction of the power consumed by traditional Bluetooth.

EnOcean covers a novel way to design wireless sensing using technologies for energy harvesting [29]. EnOcean devices communicate using ultra-low power transmissions, using sub-GHz radio frequencies. Instead of relying on conventional batteries, these sensors capture ambient energy from the surrounding environment, such as using the kinetic energy from pressing a switch, the thermal energy from temperature differences or energy from the sun. This battery-less operation is enabling maintenance-less deployment of structural sensors in Smart Homes.

Thread is an IPv6-based, low power mesh networking protocol that is made specifically for the IoT Ecosystem. Thread offers a safe and self-healing network architecture, which can dynamically re-route messages if a node fails [29]. By using IP addressing, Thread devices seamlessly fit with the existing infrastructure of the internet, fostering high levels of interoperability between a variety of Smart Home peripherals such as thermostats, locks and lighting controls.

Wi-Fi, which was based on the IEEE 802.11 standards, is the ubiquitous protocol for high speed wireless internet access [30]. Operating in the 2.4 GHz and 5 GHz frequencies, Wi-Fi offers huge data throughput capabilities and is indispensable for streaming audiovisual data, facilitating telehealth video consultations and supporting your backhaul for Smart Home gateways. However, because of its high power usage, it is not previously suitable for long-term use in small, battery-operated biosensors.

Z-Wave is a proprietary wireless communication standard that is designed for home automation [31]. Operating in the sub-GHz frequency spectrum, Z-Wave does not suffer from the excruciating problem of spectrum congestion in the 2.4 GHz band, and provides a better signal penetration through walls and structural barriers. It makes use of a mesh topology in which devices route the command through neighboring nodes, essentially lengthening the network's range throughout large residences, while preserving the ultra-low power draw.

Zigbee is an open standard based on the global 2.4 GHz bandwidth standard called 802.15.4. Like Z-Wave, it is based on a self-healing mesh network standard [29] to achieve the reliable data routing. Zigbee is intended for low data rate and low power applications. It uses certain application profiles to standardize the interaction between devices, so that sensors and actuators made by different companies will integrate well into one home automation system. DASH7 is an open source wireless protocol targeted for long distance low power applications [29]. Operating in the sub-GHz regions,

DASH7 uses asynchronous communication and burst data transmission to achieve a range of several kilometers. It uses these advanced spread spectrum

modulation to reduce the interference from this technology, making it an ideal fit for ambient monitoring in large retirement communities, or even smart cities.

LoRa is Short for Long Range which is a protocol for massive IoT deployment applications with plenty of geographical coverage [31]. It uses the Chirp Spread Spectrum modulation to send small amounts of data over large distances (indeed, it often sends data over a dozen kilometers in urban areas) on minimal battery power. LoRa is very useful for some applications such as GPS tracking of dementia patients outside or in the community wide environment sensing applications, both the star and mesh topologies using the LoRaWAN framework.

Cellular IoT technologies, such as LTE-M and Narrowband IoT, use existing telecommunications infrastructure to offer deep indoor coverage and broad area coverage. Operating on licensed frequency bands, one such set of protocols eliminates the need for local Wi-Fi gateways, linking devices directly to cellular towers [32]. Furthermore, the ushering in of 5G network brings along a new standard called ultra-reliable low-latency communication which is expected to be the soul-changing innovation in real-time telemedicine, high-definition remote monitoring, and the deployment of caregiving robots.

Mioty is a new protocol designed for massive IoT applications that may be vulnerable to high interference [32-33]. It uses a patented technology to split telegraphy into smaller sub-packets sent on different frequencies and time slots. This provides for exceptional levels of resilience and reliability, and enables communication of thousands of sensors simultaneously in dense smart building implementations.

Lastly, Sigfox is an ultra-narrowband protocol that must be used to connect low-power devices with vast distances in an absolutely minimal energy consumption [33]. By using extremely narrow frequency bands, Sigfox has a tremendous range and deep structural penetration, though strictly limited to very low data rates. It is an ideal solution for passive monitors for the environment where we only need to report a few bytes of status data per day. These wireless Smart Home protocols are demonstrated at Figure 8:

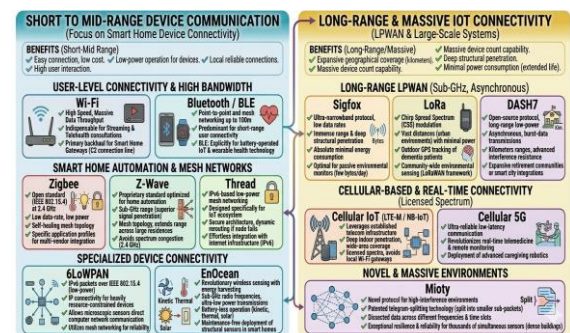


Fig. 8. Overview and summary of wireless Smart Home protocol integrated by Internet of Things

A Graphical comparison of existing networking technologies regarding network characteristics is presented at Figure 9 below [29]:

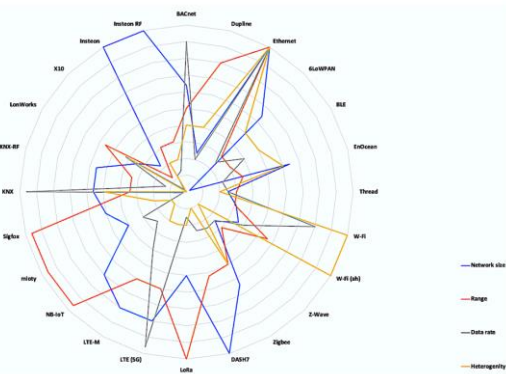


Fig. 9. Characteristics of current networking technologies [29]

#### IV. AMBIENT ASSISTED LIVING DEVICES AND HEALTHCARE APPLICATIONS

The tangible interface of a Smart Home is an array of special Ambient Assisted Living devices [34]. These devices are designed to facilitate the self-sufficiency of the elderly and address the specific vulnerabilities of the senior individual by turning the dwelling into an intelligent care environment. Personal Emergency Response Systems are some of the most established of all assistive technologies. Initially designed as simple wearable pendants - with push button activation - modern systems have become sophisticated wearables with triaxial accelerometers, gyroscopes and GPS tracking. These types of devices allow for two-way communication with centralized monitoring stations. Because even the best elderly individuals can forget to wear these devices especially if they are cognitively impaired, there is an increasing interest in Smart Homes to use ambient fall detection systems [35]. These systems use acoustic sensors, which recognize the unique sound signatures of a fall, passive infrared sensors that monitor unusual motion events, and visual systems that verify fall-related events. Multi-modal approaches integrate these sensors to significantly reduce false alarms as when a possible fall is detected, the devices can automatically turn on a camera and microphone to determine the user; they can also automatically dispatch emergency services if needed as seen in Figure 10.

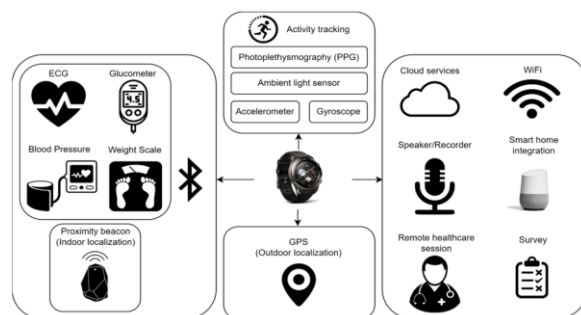


Fig. 10. Prospective applications of sensor and antenna technologies in smart devices [35]

Continuous physiological monitoring is a gigantic leap forward to the treatment of chronic diseases. Telemedicine devices are a way to collect and transmit vital health metrics directly to healthcare professionals [36]. Wearable technology is available using photoplethysmography and galvanic skin response provides continuous telemetry of heart rate, blood oxygen saturation and stress levels. To further decrease the workload of the user, non-contact monitoring systems have been developed. Smart beds which are embedded with a pressure sensor matrix, as well as piezoelectric materials, are able to trace sleep staging, nocturnal movement rates and respiratory abnormalities such as sleep apnea, without having to be attached to the patient itself [37]. In addition, state-of-the-art radio-frequency sensors can be used to measure the minute displacement of the chest cavity in order to determine respiration and heart rates several meters away.

Medication management systems help solve the critical threats of polypharmacy. Automated dispensing devices are programmed to release precise drug dosages of precise amounts at exact intervals using visual and auditory stimuli to notify the user [38]. Advanced systems capture dispensations to track compliance, conduct checks on which drugs the user is taking and what interactions may occur with other medicines, based on that individual's clinical profile, and send immediate alerts if a critical dosage is missed to caregivers. Cognitive supportive technologies are those that aim to overcome memory loss and executive dysfunction [39]. Digital memory aids and visual scheduling systems work by using intuitive interfaces to break down complex daily routines into intuitive prompts. Voice activated assistants make it possible to control the home environment hands-free, and the approach can be used by people with mobility or cognitive limitations to control lighting, adjust thermostats, and request information based solely on natural language, as shown in Figure 11 below.

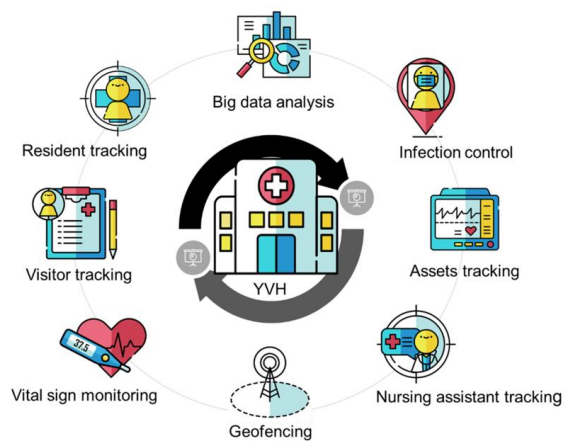


Fig. 11. Application of smart assisted living services [39]

To mitigate the psychological devastation of social isolation, Smart Homes integrate sophisticated social engagement and entertainment devices [40]. Specialized communication portals, often integrated

into smart televisions or dedicated interactive displays, facilitate high-definition video conferencing, allowing older adults to maintain robust connections with family members and participate in remote community activities. These systems are designed with simplified interfaces to accommodate lower digital literacy, fostering emotional well-being and reducing the incidence of depression.

*A. Integrated Smart Home Systems: An Exhaustive Comparative Analysis*

The imminent potential of Ambient Assisted Living can only be fully experienced if individual sensors and devices are combined into a comprehensive Smart Home ecosystem. In these types of ecosystems, heterogeneous data streams are fused together and analyzed to provide actionable clinical and environmental insights [38]. Academic institutions and commercial enterprises have created a wide variety of prototypes in the last two decades. The synthesis of these systems are evidence of the evolution of the field from rudimentary environmental automation systems to highly sophisticated artificial intelligence-driven predictive healthcare systems. Table 1 offers a broad overview of the most notable academic prototypes and commercial solutions, which describe their architectural frameworks, the modalities of sensing and analyzing.

TABLE I. COMPREHENSIVE OVERVIEW OF SMART HOME SYSTEMS AND PROTOTYPES FOR AUTONOMOUS ELDERLY LIVING

System	Institution	Modalities	Protocols	AI Strategy	Focus
Boulder Smart Home [41]	University of Colorado	Environmental (temperature, light, water flow)	Legacy hardwired systems	Artificial Neural Networks	Environmental automation, proactive energy optimization based on routine prediction.
MavHome (Managing An intelligent Versatile Home) [42]	University of Texas at Arlington	Motion (PIR), light, humidity, contact switches	Mixed (Wired and Wireless)	Statistical probabilistic modeling and pattern recognition	Proactive environmental adjustment, anticipation of resident movement to maximize comfort.
GatorTech Smart House[43]	University of Florida	RFID (keyless entry), smart bed, smart mailbox, audio/video	Middleware-based dynamic network integration	Pervasive computing middleware, automated service discovery	Support for ADLs, modular device integration, cognitive assistance via smart environments.
TigerPlace [44]	University of Missouri	Passive infrared motion, hydraulic/pneumatic bed sensors, acoustic sensors	Wireless sensor networks (WSN)	Fuzzy logic, Machine Learning for anomaly detection	Fall detection, gait analysis, predictive modeling of physical decline before acute symptom onset.
ORCATECH Life Laboratory [45]	Oregon Health & Science University	Passive IR, magnetic door switches, medication trackers	3G, Internet backhaul to centralized Cloud servers	Machine learning on longitudinal behavioral data	Early detection of cognitive decline, assessing walking speed variations, and sleep architecture.
Carleton System [46]	Carleton University	Pressure-sensitive mats, IR motion, magnetic contacts	ZigBee, Cloud computing	Four-level hierarchical threat and anomaly assessment	Security monitoring, graded emergency response based on perceived risk severity.
mHealth Wheelchair Home [47]	Academic Consortium	Wheelchair pressure pads, accelerometer, wearable ECG	ZigBee, IEEE 802.15.4, Bluetooth	Real-time threshold monitoring via localized Android interface	Continuous mobility tracking, cardiac monitoring, automated fall alerts for wheelchair users.
Integrated Clinical Telemetry [48]	Various Recent Academic Studies	ECG, Blood Pressure, SpO2, Body Temperature, Environmental	BLE, Wi-Fi, Virtual Private Network (VPN) backhaul	Clinical governance framework with threshold alerting	Comprehensive vital sign telemetry, secure physician data portals, automated clinical alerts.
GrandCare [49]	Commercial Entities	Discrete wireless ambient sensors, contact switches	Wi-Fi, Cellular	Rule-based behavioral tracking and alert generation	Remote activity monitoring, family web portals, deviation alerts, medication adherence tracking.
Independa [50]	Commercial Entity	Smart TV integration, video cameras	Wi-Fi, Cloud platforms	Cloud-based scheduling and communication logic	Social engagement, telehealth video portals, integrated medication and appointment reminders.

The Boulder Smart Home project was one of the first attempts to investigate the concept of the self-automating residence [41]. By using basic neural networks, the system learned particular daily routines of its occupants in order to proactively control the climate control, lighting, and water systems. MavHome expanded on this by using a complex set of environmental sensors and the use of statistical probabilistic modelling to be able to anticipate the movements of the resident, optimising the environment on a continuous basis [42].

The GatorTech Smart House was a huge jump in the system architecture by establishing a programmable pervasive space [43]. It used an automated middleware layer that enabled new types of sensors and actuators to be dynamically discovered and added to the network without needing to configure them. Innovations included an Rfid enabled front door for secure, keyless access, smart mailbox and advanced sleep monitoring beds, proving a Smart Home could easily evolve as new technologies became available.

TigerPlace, as built by the University of Missouri, put the focus squarely on geriatric health care and aging in place [44]. Designed as an environment to live in, it heavily relied on non-intrusive passive sensors, such as motion detectors and hydraulic bed sensors. Using fuzzy logic and machine learning algorithms to crash their longitudinal sensor data, TigerPlace were able to establish baselines against normal resident activity. The system showed remarkable success in identifying subtle variations in walking speed, restlessness during sleep and overall mobility in the apartment and was able to predict health declines and fall risks years before clinical symptoms required hospitalization.

The ORCATECH Life Laboratory was similarly dedicated to the theme of the interaction between ambient monitoring and cognitive health [45]. Using commercial passive infrared sensors and magnetic door switches, it sent information to cloud servers using 3G networks. ORCATECH's machine learning algorithms were able to analyze years of continuous data to correlate minute changes in daily behaviors, like wandering behaviors or reductions in speed, that are associated with the onset of neurodegenerative diseases like Alzheimer's. Other specialized systems target other vulnerabilities. The Carleton University system was based on security and pressure mats and magnetic switches were integrated into a four-level hierarchical alarm system to ensure that the emergency response was proportional to the severity of the detected anomaly [46]. For older people with severe mobility impairments, the mHealth Wheelchair project was unique in combining home-based environmental sensors with biometric and inertial sensors directly embedded into a wheelchair and all managed using a localized Android interface [47].

In the commercial sector, the translation of academic research has provided a number of market-ready solutions. Companies that offer mobile personal emergency response systems are based on cellular

networks and GPS to keep active seniors protected outside the home. Ambient monitoring packages from companies such as GrandCare use discrete wireless sensors to track daily routines and give family members secure web portals to see activity trends and instant alerts on deviations [48-49]. Integrated telehealth platforms, for example, those provided by Independa, use familiar interfaces, such as smart televisions, to combine the ability to video-call, program clinical appointments, and receive medication reminders, into one easy-to-use dashboard, bridging the gap between clinical care and social connectivity [50].

### B. Data Processing, Artificial Intelligence, and Automated Health Assessment

A Smart Home has a tremendous value in the application and decision-making level [25]. The perception layer produces vast amount of raw, unstructured information which is untenable without complex computational algorithms that would bring the information into perspective. The current state of the Ambient Assisted Living setting scheduled by the latest technologies incorporates the use of Machine Learning and Deep Learning to the greatest extent. It takes very strong data mining methods to distinguish a normal activity of a daily living and an outlier, like a fall or a gap of unaccounted immobility.

The sophisticated algorithms that researchers commonly use in classifications of the tricky behaviors include Hidden Markov Models, Support Vector Machines, and K-Nearest Neighbors [51]. Indicatively, information on human gait taken through the triaxial accelerometers is highly complex, as well as wildly dimensional. This data is filtered using signal processing like Empirical Mode Decomposition. This is then followed by the application of Principal Component Analysis which is used to reduce the variability of the data sets. After processing, K-Nearest Neighbors algorithms are capable of recognizing the walking patterns with fair accuracy and this feature enables the system to independently identify shuffling gait of the early-stage Parkinson diseases [52].

Other than in physical kinematics, machine learning finds wide use to evaluate cognitive deterioration. Monitoring the behavior of people in the form of contacts and measurements on magnetic door sensors and evaluating the amount of time an individual spends in a certain spatial area, algorithms can detect wandering or exploitive, excessive and unexpected stasis [53]. This enables the system to segregate residents into particular mental health groups. Moreover, natural language processing and the use of audio sensors is capable of foot patrol behavioural biometrics. The system can utilize the speech using the non-invasive biomarker, speech measures, by percentages to quantify the overall volume and frequency of human speech in the household, followed by univariate regression analysis to discover the first symptoms of clinical depression, severe social

isolation, and cognitive withdrawal. This scheme at Figure 12 appears as follows:

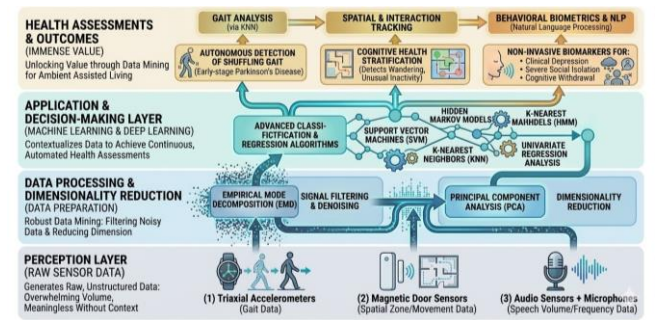


Fig. 12. Ambient assisted living: Data to Decision pipeline

### V. CHALLENGES, ETHICAL CONSIDERATIONS, AND FUTURE DIRECTIONS

Regardless of the enormous technological advances that have been observed in the last ten years, the widespread adoption of Smart Homes in elderly individuals have their infrastructural, societal, and ethical challenges that should be addressed in order to achieve maximum potential. The most complication to the mass-valuable adoption is the maintenance of information personal security and cybersecurity [54]. Smart Homes produce huge, continuous bodies of extremely sensitive physiological, behavioral and audiovisual information. Elderly people can be considered especially vulnerable to data exploitation, social engineering, or cyberattacks because older adults can have cognitive problems or simply lack digital literacy. In case of a network failure of a smart house, malicious attackers might have access to live video feeds or intercept communications or tamper with the medical telemetry and pharmaceutical schedules in an evil way [55].

As a result the introduction of military based end-to-end encryption systems like AES-256, effective multi-factor authentication systems and secure data routing are not only necessary ethical considerations but is a basic human right to autonomy and personal dignity [56]. Constant monitoring of the surroundings of the elderly people may turn them into data points and create an atmosphere that belongs to a severely intrusive product. The technologies in the field of AI as an Assisted Living should be guided by a very strong sense of human-centered design. The systems should be constructed so as to uphold dignity, maintain a clear and continuous working informed consent, and offer the user an immensely fine-tuned control over the kind of particular data gathered and shared out with people [57].

Losses due to technological constraints in terms of interoperability are still limiting the market growth. The integration of heterogeneous devices of a Smart Home is a very intricate one [58]. There is currently no globally accepted standard of communication, so the current sphere of global communication is highly siloed and proprietary and cannot communicate with any other sphere. This disintegration is very much higher

cost infrastructures, maintenance will be a lot more difficult and consumers will not have much choice. Moreover, telemetry power requires a lot of energy, and the user needs nonstop power supply. Although this problem is alleviated to a certain degree by the low-power wide-area network protocols and energy-harvesting sensors, operation of the power distribution between dozens of wireless nodes still poses a rather challenging logistical challenge [59]. Moreover, there is a transmission latency and enormous network bandwidth the broadscale communication of raw sensor data to central processing entities such as cloud servers.

A significant challenge also lies in overcoming the digital divide and user resistance [60]. A prevailing technology-push approach exists within the industry, wherein engineers design highly complex systems based on technological feasibility rather than the actual desires and capabilities of the elderly end-users [61]. Resistance to innovation is notably high among older cohorts due to confusing user interfaces, the high cost of acquisition, and a lack of perceived tangible value as exhibited in Figure 13 .Successful adoption on a mass scale demands a shift in thinking to retrofits that are simple to use and integrate into the home's existing decor without causing anxiety, technology fatigue, or stigmatization.

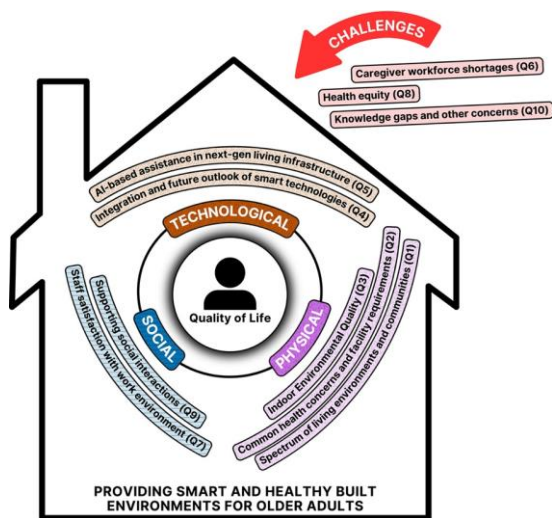


Fig. 13. Figure Challenges for Smart Home implementation scheme regarding the elderly

To overcome the problems of latency, bandwidth consumption and privacy, the future architecture of Smart Homes is fast shifting towards Edge Computing and Edge Intelligence [62]. By moving processing capabilities away from centralized cloud servers and directly to local gateway servers, or even the sensor nodes themselves, data can be processed entirely on-site. In an edge computing paradigm, only anonymized metadata, summarized health trends or critical emergency alerts are sent to the external cloud. This architecture greatly strengthens privacy, greatly cuts back on bandwidth needs, and can ensure that the Smart Home can still make life-saving decisions even if the external internet connection is severed.

Furthermore, the combination of Generative Artificial Intelligence and Large Language Models is expected to revolutionize human-computer interaction as part of Ambient Assisted Living environments [63-64]. Generative artificial intelligence can power empathetic, highly contextual conversational virtual companions that provide vital cognitive stimulation, combat the effects of loneliness, and help manage complex daily schedules through intuitive, natural dialogue rather than rigid command interfaces. Additionally, advanced neural networks, such as Generative Adversarial Networks, can be utilized by researchers to generate massive datasets of synthetic, fully anonymized healthcare profiles. This allows for the rigorous training of highly accurate predictive health models without ever exposing real patient data to the risk of privacy breaches.

#### VI. CHALLENGES, ETHICAL CONSIDERATIONS, AND FUTURE DIRECTIONS

A shift towards the aging in place has become one of the cornerstone paradigm shifts in the field of gerontology in which geriatric care is no longer centered around a model of reactive and episodic forms of clinical intervention but rather centered around continuous monitoring of the surrounding environment. Through the Internet of Things and Ambient Assisted Living, Smart Homes can help older adults maintain their autonomy, independence and dignity as they safely address physical and cognitive disabilities that accompany aging. The integration of the various technological resources, including passive infrared fall sensors, contactless vital signs monitors, automatic dispensers of medicines and immersive cognitive tools is successful in terms of covering an extended area of both somatic and psychological decreases. Nevertheless, systematic and infrastructural impediments are currently overwhelming the successful implementation of completely integrated pervasive smart environments as a technological standard of healthcare.

To overcome these issues is to abandon closed and proprietary ecosystems in favor of universal and open standards in order to encourage a free flow of interoperability between different devices. Moreover, the engineering and medical communities need to adopt a highly humanistic design philosophy. This implies that digital inclusivity should be valued, balancing always-on safety surveillance and individual privacy has to be regarded, and data structures need to be fortified against the future cybersecurity challenges. In the future, the magnitude of Smart geriatric care will be driven by the invention of artificial intelligence and localised processing. With the introduction of Edge computing, processing power directly in the living space, and Generative language models promising -like levels of empathy in system interface and interaction the Smart Home will expand beyond its currently passive-monitor mode. Instead, it will actively engage, evolve and respond to the evolving demands of its residents and, ultimately,

establish itself as a life-sustaining, essential element of healthcare in the future.

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