MOBILITY AND HANDOFF MANAGEMENT IN 5G

Abstract

This paper offers an overview of the current advancements in Operating Systems (OSs) for Wireless Sensor Networks (WSNs). In recent years, the research community has shown significant interest in WSNs due to their diverse applications, ranging from battlefield deployment and industrial process monitoring to home automation and environmental observation. WSNs pose unique challenges as they operate in dynamic environments where nodes can fail due to harsh conditions and limited battery resources. These networks consist of small, resource- constrained devices known as motes, characterized by restricted memory and computational capabilities. Additionally, WSNs often operate autonomously, making it difficult to replace sensor motes once deployed. Therefore, a primary objective is to optimize the lifespan of these sensor motes.These distinctive characteristics of WSNs impose specific challenges on OS design, diverging from conventional OS design principles. This survey aims to shed light on the key concerns related to OS design in WSNs and to evaluate the strengths and weaknesses of contemporary OSs in this context, considering the evolving requirements of WSN applications. We examine the state-of-the-art in WSN operating systems across various aspects, including OS architecture, programming model, scheduling mechanisms, memory management and protection, communication protocols, resource sharing, support for real-time applications, and additional functionalities. Our assessment encompasses both real-time and non-real-time OSs designed for WSNs.

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Operating Systems for Sensor Networks

I. INTRODUCTION

Progress in networking and integration has paved the way for compact, adaptable, and budget-friendly nodes capable of interacting with their surroundings and each other via sensors, actuators, and communication interfaces. Today, we witness the emergence of single-chip systems that seamlessly incorporate energy-efficient CPUs, memory, as well as radio or optical communication, alongside MEMS-based sensors integrated directly on the chip.

This cost-effectiveness of these integrated systems has opened doors to establishing embedded networks comprising thousands of interconnected nodes. These networks find application in a wide array of scenarios, including environmental and habitat monitoring, structural analysis through seismic measurements, as well as object localization and tracking.

II. DESIGN ISSUES

1. **Architecture:** The structure of an operating system (OS) defines its organization. The OS architecture plays a pivotal role in determining the size of the OS kernel and how it delivers services to application programs. Several well-known OS architectures include the monolithic architecture, microkernel architecture, virtual machine architecture, and layered architecture.In the case of a monolithic architecture, there is essentially no inherent structure. The OS services are implemented independently, with each service offering an interface for other services. This approach allows the bundling of all necessary services into a single system image, resulting in a smaller OS memory footprint. One advantage is that module interaction costs are low. However, monolithic architectures have significant drawbacks, including being challenging to comprehend, modify, unreliable, and difficult to maintain. These limitations make monolithic kernels an unsuitable choice for modern sensor nodes. An alternative option is the microkernel architecture, where the kernel provides minimal functionality. Consequently, the kernel size is significantly reduced. Most OS functions are delivered through user-level servers, such as file servers, memory servers, and time servers. In this setup, if one server fails, it doesn't cause the entire system to crash. Microkernel architectures offer improved reliability, ease of extension, and customization. However, they may suffer from reduced performance due to frequent user-to-kernel boundary crossings. Nevertheless, microkernels are a favored design choice for many embedded OSs, given their compact kernel size and the typically fewer context switches in wireless sensor network (WSN) applications, resulting in fewer boundary crossings compared to traditional systems. Another architectural option is the virtual machine architecture, where virtual machines, resembling hardware, are presented to user programs. These virtual machines encompass all necessary hardware features, offering portability as a key advantage. However, they can suffer from poor system performance as a notable disadvantage. The layered OS architecture organizes services into layers. This approach offers advantages like manageability, ease of understanding, and reliability. However, it may not be very flexible in terms of OS design. For an OS designed for a Wireless Sensor Network, the architecture should prioritize a small kernel size, thus minimizing memory usage. It should also allow for kernel extensions when necessary and exhibit flexibility, loading only the services required by the application onto the system.

2. **Programming Models:** The programming model supported by an operating system (OS) plays a crucial role in shaping the approach to application development. In the context of typical Wireless Sensor Network (WSN) OSs, two prevalent programming models are utilized: event-driven programming and multithreaded programming. Multithreading, while familiar to many programmers, is inherently resource-intensive, making it less suitable for devices with stringent resource constraints like sensor nodes. Therefore, it is often considered suboptimal for such devices. On the other hand, event-driven programming is deemed more appropriate for computing devices with limited resources, but it may not be the most convenient choice for traditional application developers due to its non- standard nature. In response to these challenges, researchers have directed their efforts towards devising a lightweight multithreading programming model tailored for WSN OSs. Many modern WSN OSs now incorporate support for this multithreading programming model, which we will explore in greater detail later.

3. **Scheduling:** CPU scheduling plays a pivotal role in determining how tasks are executed on a CPU. In traditional computer systems, the primary objective of a scheduler is to minimize latency, maximize throughput and efficient resource utilization, and ensure equitable task execution. In the context of Wireless Sensor Networks (WSNs), the choice of a scheduling algorithm typically hinges on the specific characteristics of the application. Real-time scheduling algorithms are utilized for applications with strict, time-critical requirements, while non-real-time scheduling algorithms are sufficient for applications with more flexible timing needs. Given that WSNs are deployed in both real-time and non-real-time scenarios, a WSN operating system must provide adaptable scheduling algorithms capable of accommodating a range of application demands. Moreover, an ideal scheduling algorithm for WSNs should prioritize efficient use of both memory and energy resources.

4. **Memory Management and Protection:** Memory management in a traditional operating system involves the strategy used to allocate and deallocate memory for different processes and threads. There are two commonly used memory management techniques: static memory management and dynamic memory management. Static memory management is a straightforward approach and proves useful when dealing with limited memory resources. However, it results in inflexible systems because it does not allow for runtime memory allocation. In contrast, dynamic memory management offers a more flexible system as it allows memory to be allocated and deallocated at runtime. This flexibility can be advantageous in various scenarios. Another critical aspect is process memory protection, which safeguards one process's address space from interference by another. In early sensor network operating systems, memory management was not available. These initial operating systems for Wireless Sensor Networks (WSNs) assumed that only a single application would execute on a sensor mote, eliminating the need for memory protection. However, with the expansion of new application domains for WSNs, contemporary WSN operating systems now provide support for multiple threads of execution. As a result, memory management becomes a crucial consideration in the design of a WSN OS.

5. **Communication Protocol Support:** In the realm of operating systems (OS), communication encompasses both inter-process communication within the system and communication with other nodes in the network. In the context of Wireless Sensor Networks

(WSNs), which operate in a distributed environment, sensor nodes communicate not only with each other but also with external nodes in the network. All WSN operating systems provide an Application Programming Interface (API) that facilitates communication for application programs. It's worth noting that a WSN can consist of heterogeneous sensor nodes with varying capabilities. Therefore, the communication protocol offered by the OS must be designed to accommodate this heterogeneity. In the context of network-based communication, the OS should include implementations of transport, network, and MAC layer protocols to enable seamless communication within the network. These protocols are essential for ensuring data exchange and coordination among the diverse sensor nodes in a WSN.

6. **Resource Sharing:** An essential role of an operating system (OS) is managing the allocation and sharing of resources, a particularly crucial task when multiple programs are running concurrently. In today's landscape, most Wireless Sensor Network (WSN) OSs incorporate some form of multithreading, necessitating effective resource sharing mechanisms. Resource sharing occurs both in terms of time, such as scheduling processes/threads on the CPU, and in terms of space, like storing data in system memory. In certain scenarios, there is a need for controlled, sequential access to resources. This is achieved through the utilization of synchronization primitives, which ensure that access to shared resources is coordinated and serialized, preventing conflicts and data corruption.

III. EXAMPLES OF OPERATING SYSTEMS

1. **Emeralds:** EMERALDS is an extensible microkernel developed in C++ specifically tailored for embedded, real-time distributed systems. It's designed to cater to embedded applications that operate on relatively slower processors, typically ranging from 15 to 25 MHz, and possess limited memory resources, typically in the range of 32 to 128 kB. One of its notable features is its support for multithreaded processes and comprehensive memory protection. These processes are managed and scheduled using a combination of the earliest deadline first (EDF) and rate- monotonic (RM) scheduling algorithms. EMERALDS adopts a unique approach for device drivers by implementing them at the user level, while interrupt handling occurs at the kernel level, enhancing efficiency and modularity. For synchronization among processes, EMERALDS employs semaphores and condition variables, and it incorporates priority inheritance to prevent potential deadlock situations. It also provides full semaphore semantics to minimize context switching, optimizing system performance. Interprocessor communication (IPC) is a key aspect of EMERALDS, and it is achieved through message passing, mailboxes, and shared memory. Notably, the IPC mechanisms are optimized for efficient intranode and intertask communication. Interestingly, EMERALDS employs global variables instead of mailboxes for exchanging information between tasks, a design choice made to streamline message handling. It's important to note that EMERALDS does not encompass networking functionalities, as its primary focus is on meeting the specific requirements of embedded, real-time distributed systems with resource-constrained hardware.

2. **PicOS:** One notable characteristic of operating systems for microcontrollers with limited RAM is their emphasis on conserving memory allocation for processes or threads. PicOS, written in C, is specifically designed to run on microcontrollers with constrained on-chip RAM, often as low as 4 kB. In PicOS, a distinctive approach is taken where all tasks

share a common global stack and operate as coroutines. These coroutines have multiple entry points and implicitly manage control transfer, a departure from conventional multitasking methods. Each task in PicOS resembles a Finite State Machine (FSM), with state transitions triggered by events. This FSM-based approach is particularly effective for applications with a reactive nature, where the primary function is to respond to events rather than intensive data processing or computation. The CPU cycles are time-shared among multiple tasks, but preemption of tasks can only occur at the boundaries of FSM states. PicOS boasts minimal resource requirements and supports multitasking, featuring a flat process structure. However, it may not be the most suitable choice for real-time applications that demand strict timing constraints and guarantees.

3. **SenOS**: SenOS is an operating system built around the concept of Finite State Machines (FSM), consisting of three core components:

   - **Kernel:** The kernel is at the heart of SenOS and houses two vital elements—an event queue and a state sequencer. The state sequencer patiently awaits input from the event queue, which operates as a First-In-First-Out (FIFO) queue.

   - **State Transition Table :** SenOS relies on a state transition table that holds critical information regarding state transitions and their corresponding callback functions. Each state transition table defines an application. By utilizing multiple state transition tables and seamlessly switching between them, SenOS supports the concurrent execution of multiple applications.

   - **Callback Library:** This component comprises a library of callback functions. When an event is received, it is enqueued in the event queue. The first event in the queue is scheduled, initiating a state transition, and consequently, invoking the associated callback functions.

   SenOS employs a statically built kernel and callback library, storing them in the flash ROM of a sensor node. However, the state transition table stands out as a dynamic element that can be reloaded or modified during runtime, tailored to the specific needs of an application. This FSM-based design offers inherent advantages in terms of enabling concurrency and facilitating reconfiguration.

   Moreover, SenOS is readily extensible, particularly for network management purposes, making it adaptable to a range of application scenarios.

IV. NODE LEVEL SIMULATORS

Node-level design methodologies are commonly linked with simulators aimed at modeling the behavior of individual nodes within a sensor network. Simulation serves as a valuable tool for designers, allowing them to efficiently evaluate the performance aspects of potential algorithms. This evaluation encompasses parameters such as timing, power consumption, bandwidth utilization, and scalability. Simulation provides a practical means to assess these aspects without the need for physical hardware implementation, avoiding the complexities associated with real-world physical phenomena. A typical node-level simulator comprises several key components:

1. **Sensor Node Model:** In a simulator, a node serves as a versatile entity, functioning as a software execution platform, a sensor host, and a communication terminal all in one. To facilitate designers in concentrating on application-level code, a node model typically offers or emulates essential components, including a communication protocol stack, sensor behaviors (such as simulating sensing noise), and services akin to an operating system. In instances where nodes exhibit mobility, the simulator also models the positions and motion attributes of these nodes. Furthermore, if energy-related factors are integral to the design considerations, the simulator incorporates modeling for node power consumption. This comprehensive approach ensures that designers can effectively assess and refine their designs while abstracting away the intricacies of lower-level node functionalities.

2. **Communication Model:** The way communication is represented in simulators can vary based on modeling intricacies. In more comprehensive simulators, communication is modeled at the physical layer, which includes simulations of RF (Radio Frequency) propagation delay and the handling of simultaneous transmission collisions. Alternatively, simulations may focus on the MAC (Medium Access Control) layer or the network layer. In such cases, stochastic processes might be employed to simulate lower-level behaviors, providing a different level of abstraction for communication modeling.

3. **Physical Environment Model:** A fundamental aspect of the environment in which a sensor network operates is the underlying physical phenomenon of interest. Modeling this environment can be approached with varying levels of detail. For instance, when dealing with a moving object in the physical world, it may be simplified as a point signal source in the simulation. The motion of this point signal source can then be represented through differential equations or interpolated from a predefined trajectory profile. In scenarios where the sensor network operates passively and does not impact the environment's behavior, the environment can be simulated independently or even pre-stored in data files for sensor nodes to access. However, if the network's functionality extends beyond sensing and includes actions that influence the environment's behavior, a more tightly integrated simulation mechanism becomes necessary to capture these complex interactions effectively.

4. **Statistics and Visualization:** Collecting simulation results for subsequent analysis is a crucial step in the simulation process. Simulations often aim to extract global properties from the individual node executions, making the visualization of these global behaviors highly significant. An effective visualization tool should empower users to conveniently observe various aspects on demand. This includes insights into the spatial distribution and mobility patterns of nodes, the establishment of connectivity among nodes, the quality of links, the routes and delays in end-to-end communication, dynamic spatio-temporal phenomena, sensor readings recorded by each node, the states of sensor nodes, and essential node parameters such as their remaining battery power, which impacts node lifetime. Having access to these visualizations enhances the understanding and interpretation of simulation outcomes.

V. PERFORMANCE AND TRAFFIC MANAGEMENT ISSUES

Wireless Sensor Networks (WSNs) have reached a level of maturity that makes them a viable technology for monitoring non-critical systems across various environments, including industrial, office, and domestic settings. As a result, we anticipate a growing number of applications harnessing WSN technology, each with unique requirements for the underlying network. Given the inherent characteristics of WSN communications, achieving these diverse network requirements involves employing a range of communication tools. However, the expanding array of tools, coupled with their increasing complexity, makes it challenging to determine the most suitable tool for a specific application in a given deployment. In a WSN, which comprises numerous densely deployed sensor nodes interconnected wirelessly, data retrieval is triggered by events. When an event is detected, the data associated with that event must be transmitted to a designated sink node, often serving as the data collection hub. It's important to note that the sink node can become a bottleneck in the network, particularly when dealing with heavy data traffic, potentially leading to congestion issues and data loss, including critical data. To address this challenge, an approach based on soft computing, specifically Neural Networks (NNs), is proposed as a congestion controller. The NN operates using a wavelet activation function, which effectively regulates the traffic within the WSN. This approach, referred to as Modified Neural Network Wavelet Congestion Control (MNNWCC), encompasses three primary activities:

- Detecting congestion by analyzing congestion level indicators.
- Estimating traffic rates, with adjustments made to the upstream traffic rate to prevent congestion in subsequent cycles.
- Enhancing Quality of Service (QoS) metrics, such as Packet Loss Ratio (PLR), Throughput (TP), Buffer Utilization (BU), and Network Energy (NE), to improve overall network performance.

Simulation results demonstrate that the proposed MNNWCC approach effectively prevents network congestion and enhances the QoS of the WSN, ensuring the reliability and efficiency of data transmission in event-driven scenarios.

VI. PERFORMANCE MODELLING OF WSNS

In wireless sensor networks, a critical challenge revolves around the limited availability of energy within network nodes. Effectively managing this energy resource is of paramount importance. One widely adopted energy-saving strategy involves placing nodes in a sleep mode, characterized by reduced power consumption and diminished operational capabilities. In this study, we have developed a Markov model to represent a sensor network where nodes have the ability to transition into a sleep mode. We leverage this model to delve into the system's performance across key parameters, including energy consumption, network capacity, and data delivery latency. Additionally, our model enables us to explore the trade-offs that exist between these performance metrics and the dynamic behavior of sensors transitioning between sleep and active modes. Our analytical results demonstrate a close alignment with simulation outcomes across a diverse range of system scenarios, underscoring the accuracy and reliability of our approach. This work sheds light on the intricate dynamics of energy management in wireless sensor networks, offering valuable insights for optimizing their performance and resource utilization.

VII. EMERGING APPLICATIONS AND FUTURE RESEARCH DIRECTIONS

Wireless sensor networking technology has found widespread use in both commercial and military applications, primarily for sensing and data collection purposes. These networks offer the advantage of self-configuration, self- healing capabilities, and easy deployment, making them a compelling alternative to centralized approaches. While many existing networking solutions for sensor networks primarily focus on communication aspects, they often fall short in addressing the critical issue of data security within these networks. As sensor networks are increasingly deployed for emerging applications involving sensitive data and their integration with cyberspace, the imperative to address the security requirements of wireless sensor networks becomes paramount. The design of security solutions for these networks presents a formidable challenge due to the inherent resource constraints of sensor nodes and the distributed nature of network architecture. This chapter serves as an overview of emerging sensor networks that deal with sensitive data, alongside a discussion of some proposed security solutions aimed at safeguarding these networks. The future advancements in sensor node technology must prioritize the development of highly powerful yet cost-effective devices. This approach will enable their use in a wide array of applications, including underwater acoustic sensor systems, cyber-physical systems reliant on sensing, time- critical applications, cognitive sensing and spectrum management, as well as security and privacy management. In this section, we explore the various possibilities for further advancement in Wireless Sensor Network (WSN) applications.

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VIII. NETWORK DEPLOYMENT TYPES

While 5G technology has been standardized, it offers a multitude of options, allowing different network operators to deploy it in unique ways. The choice of these options depends on several factors, including the spectrum licensed to an operator, the geographic area they serve (which encompasses terrain and user density), the capabilities of the equipment they utilize, and various business considerations such as cash flow and decision- making processes. The 3rd Generation Partnership Project (3GPP) has defined options that encompass both 4G and 5G technologies concerning the Radio Access Network (RAN) and Core Network (CN). These options serve as guidelines for operators as they transition from their existing 4G deployments to 5G deployments. Typically, operators are expected to initially deploy 5G New Radio (NR), allowing 4G RAN and 5G NR to coexist. Subsequently, they would deploy 5G Core networks. This progression implies that 4G+5G handsets would be introduced first, capable of connecting to both 4G eNodeB (eNB) and 5G gNodeB (gNB). In the LTE era, both RAN and CN had to adhere to LTE standards. However, 5G introduces greater flexibility. For instance, 4G RAN can be combined with 5G Core, or 5G NR can be combined with 4G Evolved Packet Core (EPC). This flexibility results in two primary deployment scenarios:

1. **Standalone (SA):** This scenario employs only one radio access technology, either LTE radio or 5G NR. Both control and user planes are routed through the same RAN element. This approach may simplify deployment and network management for operators. Inter-RAT (Radio Access Technology) handover is required for seamless service continuity. Within SA, there are options such as option 1 (EPC + 4G eNB), option 2 (5GC + 5G

gNB), and option 5 (5GC + 4G Next-Generation eNB).

2. **Non-Standalone (NSA):** In this scenario, multiple radio access technologies are combined. The control plane is directed through a master node, while the data plane is split between the master node and a secondary node. Thereis tight interworking between 4G RAN and 5G NR. Under NSA, options include option 3 (EPC + 4G eNB master+ 5G gNB secondary), option 4 (5GC + 5G gNB master + 4G Next-Generation eNB secondary), and option 7 (5GC + 4G Next-Generation eNB master + 5G gNB secondary).

IX. INTERFERENCE MANAGEMENT IN 5G

In the ever-evolving landscape of modern technology, wireless communication has undergone a remarkable transformation from traditional systems to the realm of Fifth Generation (5G) cellular networks. This innovative concept of 5G networks represents a convergence of diverse devices and machines, promising substantial improvements compared to its predecessors. It seeks to enhance user experiences and cater to the growing demands for efficient communication. Central to the evolution of 5G technology is the deployment of a network comprising small cells and novel technologies previously unexplored. This network design incorporates a medley of approaches, including Heterogeneous Networks (HetNets), Device-to-Device (D2D) communication, Internet of Things (IoT), Relay Nodes (RNs), Beamforming, Massive Multiple Input Multiple Output (M-MIMO), millimeter-wave (mm-wave) transmission, and more. Additionally, it necessitates the enhancement of existing techniques to ensure compatibility with traditional networks. However, the convergence of these disparate technological models has led to unwanted signal interference, significantly impacting overall network performance. This review article delves into the intricacies of interference issues observed and studied across various structures and techniques within the realm of 5G and beyond networks. The focus is on exploring interference effects in HetNets, RNs, D2D communication, and IoT. As part of an in-depth literature review, we examine different types of interferences associated with each approach, drawing insights from state-of-the-art research in the field. Through comprehensive discussions in each section, we aim to provide fresh perspectives on managing interference issues in next-generation networks, ultimately contributing to a more robust system. In the context of small cell wireless cellular networks, multi-tier interference is an inherent challenge due to the unique characteristics of each low-power node. These nodes generate and receive unwanted signals continuously from various nearby sources. While Half Duplex (HD) mode restricts performance by transmitting and receiving on the same frequency, Full Duplex (FD) transmission mode enables simultaneous transmission and reception on the same frequency. FD, supported by multi-antenna systems, enhances network capacity, minimizes round-trip data delivery time, and shows promise in avoiding interference and providing strong signal quality. However, the inherent delay and inefficient spectrum utilization associated with HD mode make it less desirable for new radio wireless communication. In contrast, FD offers higher throughput with lower latency and efficient spectrum usage. It enhances ergodic capacity and network secrecy. Nonetheless, it faces significant performance challenges due to interference. Therefore, the development of robust interference mitigation schemes in FD transmission is essential for realizing the full potential of future mobile networks. Common interference types in radio networks include self-interference, adjacent channel interference, intra-cell interference, and inter-cell interference. However, the scope of interference in mobile networks extends beyond these categories and varies based on deployment and transmission scenarios.

X. MOBILITY MANAGEMENT IN 5G

Over the past few decades, cellular networks have proliferated worldwide, resulting in a widespread and somewhat disorganized network landscape. To bring order to wireless networks, mobility management, including handover management, plays a crucial role. In the context of LTE networks, mobility management primarily relies on hard handover processes. However, it's important to note that LTE networks employ hard handovers, which operate on a break-before-make principle, leading to certain challenges in mobility management. Hard handovers necessitate a break in the existing connection before establishing a new one, posing some significant issues in maintaining seamless mobility. To ensure uninterrupted connectivity for User Equipment (UE), the eNB (evolved NodeB) must support this process since LTE networks do not include an RNC (Radio Network Controller) entity. However, the rapid growth in data traffic and the evolving demands of future network scenarios render these current methods insufficient. With the widespread adoption of 5G networks, several key differences emerge when comparing 4G and 5G networks. Notably, 5G networks harness the benefits of millimeter-wave (mm-wave) frequency bands, beamforming with directional antennas, higher data rates, broader coverage, reduced costs, increased capacities, and more. In the realm of mobility management, 5G networks have the potential to leverage cloud-based systems to provide enhanced services. 5G technology operates as a packet-switched system, delivering exceptional performance and efficiency. It opens up new possibilities for efficient and high- performance communication. Users can enjoy the benefits of 5G technology, including high-speed broadbandinternet connectivity, directly from their mobile devices, ushering in a new era of connectivity and communication.

XI. DYNAMIC NETWORK RECONFIGURATION IN 5G

Botnets pose a significant and pervasive cyber threat that can disrupt the continuity and delivery of network services. With the emergence of 5G networks, which introduce a multitude of connected devices with high mobility, increased data volume, and faster transmission rates, the challenge of detecting and mitigating botnet- driven attacks becomes even more daunting. To tackle this challenge, a proactive solution tailored to the dynamic nature of 5G networks is proposed. 5G networks cater to highly mobile subscribers, necessitating frequent network reconfigurations. This dynamic environment is managed through a combination of software-defined networking (SDN) and network function virtualization (NFV) techniques, ensuring seamless transitions. As 5G technology continues to evolve, it promises substantial improvements in data bandwidth and networking capabilities, enhancing the user experience in mobile communications. However, this transition also introduces new security challenges. The sheer number and diversity of 5G devices, each equipped with high mobility capabilities, create an evolved threat landscape. Among the persistent threats in 5G networks, botnets remain a potent adversary, much like in existing network infrastructures. A botnet is essentially a network comprising thousands or even millions of compromised devices, referred to as bots. These devices have fallen victim to unwitting malware infections and are remotely controlled by a Command and Control (C&C) server. Typically, the recruited bots periodically query the C&C server for instructions on whether to execute specific actions. The behavior, architecture, and communication patterns of botnets, including interactions between bots and C&C servers, are extensively documented. Distributed Denial of Service (DDoS) attacks, orchestrated by botnet owners, are among the most prevalent malicious activities today. Kaspersky Lab's Q3 2016 report revealed that botnet-assisted DDoS attacks accounted for a staggering 78.9% of all detected attacks, with the highest number recorded on August 3, totaling 1,746 attacks. Real-world examples include the Mirai and Leet botnets, which emerged in 2016, launching devastating DDoS attacks that reached up to 650 Gbps of network traffic, crippling services like Amazon and Netflix, among others.

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