Urban Area Design Analysis for Optimization

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ABSTRACT

The 2006 Quadrennial Defense Review (QDR) Report identified the ability to operate in urban terrain as a critical capability requirement. In addition, the Testing in a Joint Environment Roadmap Strategic Planning Guidance for Fiscal Years (FY) 2006-2011 identifies the need to develop representative, operationally relevant joint mission environments. Joint doctrine describes urban areas as complex, dynamic environments consisting of three distinguishing characteristics. The urban triad can be identified by the physical terrain, the non-combatant population and the physical and service infrastructure. Although the concept of what constitutes an urban area is widely understood, the design of an area sufficient for military testing/training is complex when considering the range of systems utilized by the military, the regional variability of urban areas, and cost constraints. Given financial, time, technical, and resource restraints it is unrealistic for the DOD to build cities to meet the training/testing need. Future urban testing/training areas should be of sufficient size, diversity, density, height, and depth to present realistic urban effects to sensors, communications systems, targeting systems, and personnel utilized on the urban battlefield. This paper will describe an analysis performed to determine the minimum size of the area, the minimum size of buildings and the minimum number of buildings required to generate the required effects without building an unnecessary, more expensive, number of buildings. To determine these minimums the following analyses were performed and will be described: 1). Physics analysis with respect to electromagnetic propagation in and around buildings 2). System analysis with respect to the mission and capabilities of military systems 3). Tactics, Techniques, and Procedures (TTP) employed when using the system. Additionally, the functional types of buildings that make up an urban area are described, and a notional design configuration to meet these requirements is presented.

ABOUT THE AUTHORS

Dr. Denzil Radford has over 20 years of professional experience in the areas of communications systems engineering, digital data communications, spread spectrum systems, powerline communication technologies, and wireless communications. He is currently employed by Booz Allen Hamilton and is the Systems Engineering lead for urban test capability design. Dr. Radford holds a Ph.D. in Electrical Engineering from Missouri University of Science and Technology.

Ms. Kay Mehr has over 15 years of professional experience in system architecture development and requirements definition of battlespace configurations for various military platforms (ground vehicle, aircraft, satellite and weaponry), as well as the design of the platform's communication systems. Ms. Mehr has conducted requirement development for Command, Control, Communication, Computing, Intelligence, Surveillance and Reconnaissance (C4ISR) systems, which encompasses the development of system controls, target acquisition, intelligence gathering and the design of wireless data link communications for secure networks. Ms. Mehr holds both a Master's and Bachelor's degree in Engineering from Florida State University.

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Introduction

Military operations frequently occur in complex, dense urban settings that compromise the performance of military systems. The 2006 Quadrennial Defense Review (QDR) Report identified the ability to operate in urban terrain as a critical capability requirement. In addition, the Testing in a Joint Environment Roadmap Strategic Planning Guidance for Fiscal Years (FY) 2006-2011 identifies the need to develop representative, operationally relevant joint mission environments to support developmental and operational test of new and emerging military systems.

Military operations increasingly occur in urban areas, therefore the successful operation of military systems operating in these environments grows progressively more vital. While limited representations of urban environments exist in the DoD inventory, they have deficiencies in size, complexity, realism, and control that prevent them from fulfilling the requirements of the test and evaluation community.

In Figure 1 an urban environment is shown with some important characteristics which should be represented when designing such a testing environment.

Figure 1: High Density Urban Area

Those characteristics include but are not limited to multi-story buildings, urban canyons, densely packed commercial and residential buildings, civilian activity and the electromagnetic environment of an active urban area. Joint doctrine describes urban areas as complex, dynamic environments consisting of three distinguishing characteristics. The “urban triad” can be identified by the physical terrain, the civilian population and the infrastructure that supports the civilian population. In Figure 2 Warfighters are shown utilizing their electronic equipment in this “urban triad” environment.

Figure 2: Warfighters Patrol an Urban Area

Although the concept of what constitutes an “urban” area is widely understood, the design of an area sufficient for military testing/training is complex when considering the range of systems utilized by the military, the regional variability of urban areas, and cost constraints. Given financial, time, technical, and resource restraints it is unrealistic for the DoD to build cities to meet the testing/training need. Future urban testing/training areas should be of sufficient size, diversity, density, height, and depth to present realistic urban effects to military sensors, communications systems, targeting systems, and personnel utilized on the urban battlefield.

This paper will describe an analysis performed to determine the minimum size of an urban testing environment, the minimum size of buildings and the minimum number of buildings required to generate the required effects without building an unnecessary, more expensive area. To determine these minimums the following analyses were performed and will be described;

1. Physics analysis with respect to electromagnetic propagation in and around buildings
2. System analysis with respect to the mission and capabilities of military systems
3. Tactics, Techniques, and Procedures (TTP) employed when using the system.
4. Live Urban Environment Analysis

Additionally, the functional types of buildings that make up an urban area are described, and a notional design configuration to meet the test and evaluation requirements is presented.

The Department of Defense (DoD) Test Resource Management Center (TRMC) conducted a study to determine the adequacy of the current test and evaluation facilities regarding the realistic representation of urban environments. The Urban Environment Test Capability (UETC) study included urban area terrain templates and identified capability gaps in existing facilities, which further reiterated the need for an urban environment training/testing capability.

Past Urban Studies

It is helpful to start with current information that has been gathered on urban areas in the regions of military interest. Ellefsen and Fordyce (2008) have conducted a wide range of analysis in order to characterize geographical regions where the US military may be operating in the future. With this information we can better understand the environments that military systems will be exposed to and use this information to enhance the design of those systems. They started with the analysis of a general city area and defined an analysis methodology to identify and describe the unique characteristics of an urban area. This analysis methodology is graphically depicted in Figure 3.

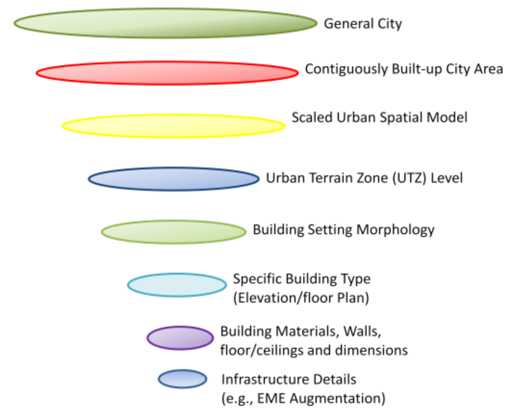

Figure 3: Urban Analysis Methodology

In the first level, they analyzed several cities within each region of interest to identify the unique characteristics of urban areas in those regions. In the second level, they identified four major land uses, (i.e. residential, commercial, industrial, and institutional) that define the region. In the third level, they studied the spatial relationship of these areas with respect to each other, in order to develop a scaled urban spatial model. A 1 kilometer (km) x 1 km Scaled Urban Spatial Model is shown in Figure 4.

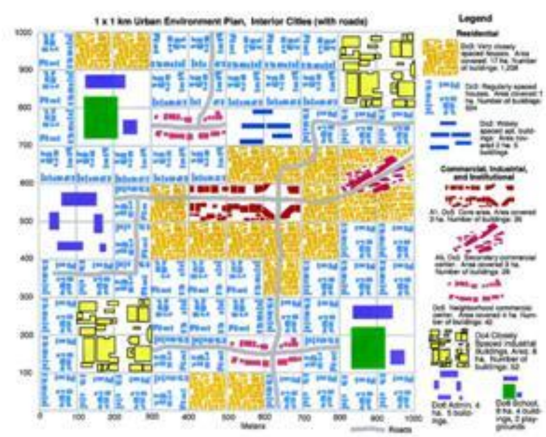

Figure 4: 1 Km X 1 Km Urban Model

In the fourth level, they further refined the scaled spatial models and defined nine Urban Terrain Zone (UTZ) areas. These nine UTZ areas bring more fidelity to the four land use types. The nine UTZ are identified by color-coded graphics on the scaled spatial models with narrative descriptions, which are tabularized below in Table 1.

While being optimal, it would be unrealistic to build an area 1 km X 1 km in size due to time and cost considerations. Our analysis indentifies the minimum size which optimizes the live urban area with respect to the proposed systems to be tested. This urban area optimization will be based on the following types of analysis; physics analysis, systems analysis, mission tactics techniques and procedures analysis and a live urban environment analysis.

Ellefsen UTZ Area	Various Significant Urban Characteristics
Dense Residential	Irregular Building Footprints, Building Separation and High Percentage of Building Footprint Coverage
Widely Space Residential	Courtyard Walls, Gates, Concrete Construction and Parking Lots
Apartment	Open Courtyards, Parking Lots, Domed Rooftops and Concrete Construction
Industrial	Metal Building Construction, Pitched Roofs, Parking Lots, and Loading Ramps
Secondary Commercial Center	Urban Canyons, Multi-Story Buildings, sidewalks, Curbs, and Street Intersection
Commercial and Institutional Center	Urban Canyons, High-rise Buildings, parking lots, and Street Intersections
Neighborhood Commercial Center	Urban Canyons, Closely-Spaced Buildings, Set-Backs and Arterial Streets
Administrative	Large, Multi-Story buildings, power distribution, courtyards, and parking lots
Academic	Large Buildings, Athletic Fields, Parking Lots, Concrete Building Construction

Table 1: Urban UTZ Areas

Physics Analysis

According to Ellefsen and Fordyce 2008, urban areas of military interest can be characterized by neighborhoods of residential, commercial and light industrial buildings covering the majority of the available land. The electromagnetic waves that comprise most wireless communications signals interact with everything in the environment, both manmade and natural. We have all experienced the phenomena of our cell phones working in one location only to have them fail just a few feet away. Significant signal loss in urban areas can be attributed to the absorption, reflection, and refraction of electromagnetic waves which are incident on exterior and interior walls of buildings.

A mathematical calculation of these losses when more than one surface is considered becomes very complex. Therefore, to begin our analysis we referred to the work of Coco, Laudani, and Pollicino which describes the results of a ray tracing simulation built to model the interference caused by densely packed buildings in an urban area. The results of Coco, et.al., simulation is graphically depicted in Figure 5, illustrating the signal attenuation in an urban area of a low power GSM handset operating at a frequency of 2.8 GHz.

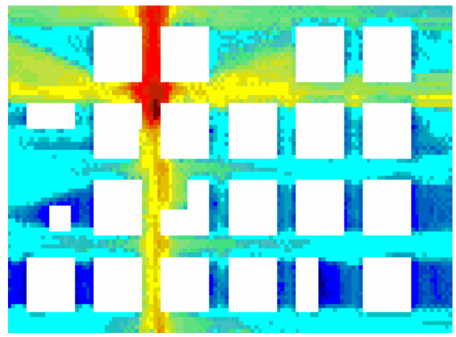

Figure 5: Ray Tracing Simulation Results

In the ray tracing model, the white rectangles represent buildings and the model predicts that within two to four buildings in any direction, the signal attenuation would be approximately 120 dB, resulting in radio dropout, indicated by the dark blue areas of the figure below. If we conclude that four buildings away from the transmitter the signal would be sufficiently attenuated as to cause radio dropout, then four buildings will be the established minimum without movement of the transmitter.

It follows that the minimum number of buildings needed in the test area would be approximately 64 with the transmitter located in the center of the area as shown in Figure 6. Furthermore, if we assume that the antenna patterns are symmetric then we would only need half the area. Therefore, an approximate minimum number of buildings required would be reduced to 32 buildings. This is illustrated in Figure 6 below, where the red star denotes the location of the transmitter, and the yellow circle indicates where the test receiver could be located.

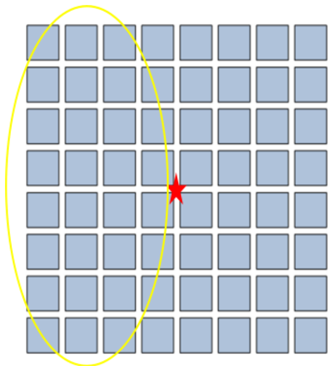

Figure 6: Minimum Number of Buildings

In order to calculate the minimum size of the urban area, the size of the buildings that would populate the environment will also have to be determined. It is known that electromagnetic waves interact with nearly everything in the environment. Figures 7 below illustrate the relationship of the size of the interfering object to the wavelength of the signal.

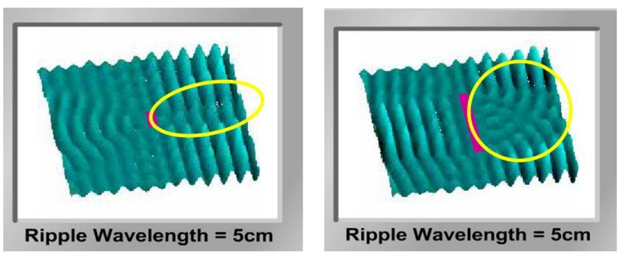

Figure 7: Small and Large RF Interference

It is evident, as indicated by the yellow circles, that the larger the interfering object is with respect to the wavelength the greater the interference. Thus, we conclude that the buildings must be realistically sized to interfere with wavelength/frequency under test. A sampling of the relevant military systems and the frequencies/wavelengths associated with each is shown in Table 2. As shown, the wavelengths associated with military systems of interest range from 0.15 meters (m) to 150 m.

System/Waveform	Frequency	Wavelength
SINCGARS	30-80 MHz	10-3.75 (m)
HAVEQUICKII	225-400 MHz	1.3-0.75 (m)
EPLRS	420-450 MHz	0.71-0.66 (m)
JTRS	2 MHz – 2 GHz	150-0.15 (m)

Table 2: Military Frequencies/Wavelengths

Buildings that are 150 m in any dimension are uncommon in the worldwide regions of military interest. Thus, it would be unrealistic to build an area with buildings of that size. However, when we look at a very common voice communication system that utilizes the SINCGARS waveform, it has a maximum wavelength of 10 m. This is a very common and realistic dimension for buildings in an urban area. Thus, for this analysis we assumed that the buildings would be 10 m in width, length and height.

The third part of the physics analysis takes into account that a test scenario would include movement of the transmitter. In Figure 8, the result of moving the transmitter the distance of two buildings in the diagonal is shown.

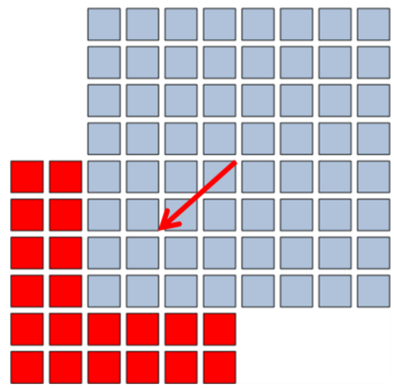

Figure 8: Transmitter Movement Considered

This scenario indicates that 20 buildings would be added to the area. As a result, our area would now contain 52 buildings. Assuming a separation of 2 m which is representative of densely packed buildings in urban areas, the total area covered by the buildings would be approximately 70 m x 120 m.

So our conclusion from the physics based analysis is that an urban environment containing approximately 52 buildings covering an area of 70 m X 120 m would be sufficient for testing a low power handheld radio system. In the following sections we will derive the area size based on system technical specifications and typical system mission requirements.

System Analysis

The types of military systems that will be used in urban environments include but are not limited to: interior building sensors, ground sensor systems, ground robotics systems, unmanned air systems (UAS), air to ground weapon systems and air to ground surveillance systems. At times these systems work as a system of systems and communicate wirelessly with each other in a dynamic network environment. A wide area network with a required 2 km line of site performance requirement is established to maintain communications with the command and control of warfighting elements.

Operators are required to establish communications with remote operated air vehicles at a distance of 8 km away and control its flight into the urban environment. The interior building sensors and ground sensor systems must communicate with the gateway sensor, which operates and communicates up to 500 m away from the command and control vehicle. The ground robotics system is required to operate 200 m away from the controlling operator. These communications are simultaneous and travel within a network to the command and control personnel and vehicles, which would encompass an 8 km x 8 km area. Air to ground missile systems are required to lock onto targets 5 km away from a target within an urban environment. Air to ground surveillance systems are capable of covering a 30 km x 30 km surveillance area.

However, air to ground weapons and surveillance systems operating at typical altitudes will produce a field of view (FOV) footprint down onto the urban environment. This footprint will require an urban area of sufficient size to impress the onboard sensors. Therefore, this analysis will investigate the operational requirements of typical surveillance and targeting sensors to determine the approximate size area that would be required to sufficiently test these systems.

Surveillance sensors are typically infrared (IR) and visible light sensors with wide FOV, (i.e. 25 degrees or more), and require large urban areas for testing. In Table 3, the diameter of the sensor view on the ground for a low altitude UAS is compared to that of a high altitude system, assuming that both have a FOV angle of 25 degrees. The equation used to calculate the diameter of the sensor view on the ground was:

$$\text{Dia} = 2 \tan(\text{FOV}/2) * \text{Alt}$$

and assumes that the sensor in looking straight down on the area as depicted in Figure 9, such that the view on the ground is a circle.

Figure 9: Sensor View on the Ground

The minimum and maximum operating altitudes for each platform were used in the calculation as well as the typical human detection requirement of 700 m for surveillance sensors.

	Min	**Max**	**Min**	**Max**	$\mathbf{H_{det}}$
ALT(m)	152	304	2500	5000	700
Dia(m)	67	135	1108	2217	310

Table 3: Sensor View Diameter

It can be seen that for the high altitude systems, these sensors would need an area of at least 1108 meters in diameter at the minimum operating altitude. At the human detection range altitude of 700 meters, the area would need to be 310 meters in diameter.

Weapon systems may contain multiple sensors used for locating and engaging targets on the ground in urban areas. In general targeting sensors would have narrower FOV ranging from 4 degrees to 10 degrees and maximum effective ranges of 3 km to 8 km depending on the sensor technology. For this analysis it was assumed that the sensor will not be looking straight down but rather will have a positive look angle as illustrated in Figure 10. The effect of the look angle is to create an elliptical shaped sensor view on the ground.

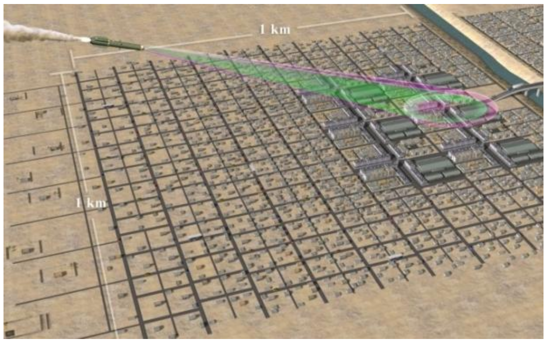

Figure 10: Elliptical Sensor View on Ground

In Table 4 below, the transverse diameter of the elliptical sensor view on the ground of three sensor types at the minimum, maximum and middle of their effective ranges, assuming a look angle of 20 degrees is shown. The IR sensor maximum transverse diameter and Semiactive Laser minimum transverse diameter are very close in value, where both dimensions are between 200 m and 250 m.

	SENSOR TECHNOLOGIES		
ALT	IR	mmW	SAL
MIN (m)	81	103	214
MID (m)	167	420	767
MAX (m)	244	818	1280

Table 4: Transverse Diameter

IR = Infrared, mmW=millimeterwave, SAL=semi-active laser.

In Figure 11 the minimum size of the sensor FOV are shown on Ellefsen's Scaled Spatial Model of an urban region to provide perspective for the reader. Recall that this is a 1km x 1km model where each major gridline is 100 m. This analysis shows that an area approximately 200 m X 200 m would be sufficient for the aerial based weapon systems.

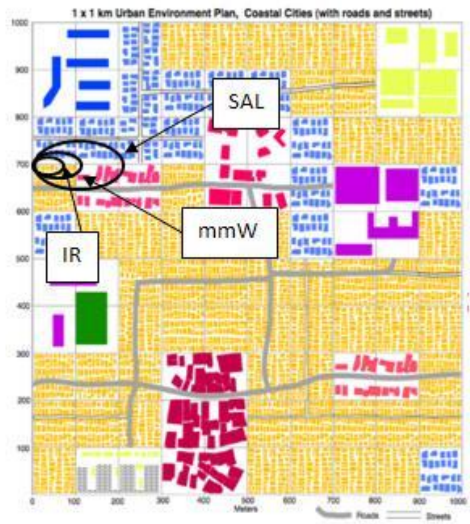

Figure 11: Elliptical View on Spatial Model

Tactics, Techniques and Procedures (TTP)

When operating the aforementioned types of systems, it is important to understand how these systems will be used in an urban environment. This information will help determine the space that is required for system testing. When analyzed individually, the systems described earlier can be tested in an area as small as one building or an area of 8 km X 8 km, if line of sight (LOS) conditions exist. Knowing that this LOS condition will not exist in a densely populated urban area, a common mission requiring a system of systems deployment is chosen for this analysis.

The Cordon and Search mission scenario is a common operational mission that is carried out in urban areas and includes a system of systems deployment. This mission is graphically depicted in Figure 12 below. A typical Cordon and Search mission involves the following scenario. A Battalion utilizes three infantry companies to execute the mission. One Company to establish the outer cordon, the second to establish an inner cordon with one platoon tasked as the battalion reserve, and a third Company to conduct the search.

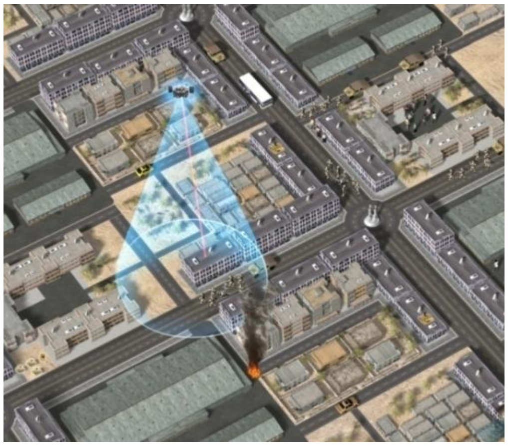

Figure 12: SOS Cordon & Search View

The Outer Cordon Company establishes the outer cordon to isolate the target from outside reinforcements by using roadblocks, patrols, and strategically placed ground sensor fields, out of direct observation range. This Company will also utilize its ground robot Intelligence, Surveillance, and Reconnaissance capability to augment the cordon. In addition, they will employ a UAS to observe activity down the enemy avenues of approach into the area. The UAS will hover over and observe its target at around 500 feet above ground level. The inner cordon company establishes blocking positions to isolate the city block containing the target building in order to prevent enemy combatants from escaping the area.

The search company enters the area and advances on a three (3) story building containing a suspected IED manufacturing facility. The company assigns one (1) platoon to breach the building using its ground robot to tap the door and then enter the building to provide reconnaissance. As each search team clears a room, they mark the room and emplace room sensors to provide warning if movement occurs. Each platoon strategically places their sensor communications gateway (e.g., on a terrace) to maximize communications back to the network controller. This gateway will communicate situational awareness back to the company commander. The commander's vehicle is located in a concealed position within the urban environment and is able to monitor the progress of the mission.

The execution of a successful test would require that the Inner Cordon Company be inside the urban environment. US Army doctrine for offensive urban operations found in FM 3-06 Urban Operations establishes frontage occupied and controlled by a Company element in a dense urban environment to be one (1) city block, which is approximately 175 m X 175 m. The depth of coverage by a Company sized element is one (1) to two (2) city blocks. This would equate to a required minimum footprint of 175 m X 350 m, and is shown in Table 5, which tabularizes the results of our analyses..

Analysis Type	Urban Area Size
Physics Analysis	70 m X 120 m
System Analysis	200 m X 200 m
Tactics Analysis	175 m X 350 m

Table 5: Urban Area Analysis Results

Based on the three analyses, we can conclude that an area of approximately 200m x 200m would be sufficient to test a wide variety of systems.

Live Urban Environment Analysis

The previous analyses established that an area of approximately 200 m X 200 m in size would provide a sufficient area to test a variety of systems. At this time, an approximation of the minimum size of the urban area and the minimum building size has been established. Now the minimum number and type of buildings must be established.

Urban areas of military interest can be characterized by neighborhoods of residential, commercial and light industrial buildings covering the majority of the available land. In Figure 13, a satellite view of an area is shown, which is prototypical of urban areas in all the regions of interest. This view shows a dense secondary commercial center, (shaded in red), bordering a heavily traveled street with densely packed residential areas, (shaded in blue), abutting against the commercial area. In close proximity to this area, is a light industrial area (shaded in purple) which is adjacent to some apartment buildings.

Figure 13: Prototypical Urban Area

It follows that the notional urban area should contain elements of these UTZ areas, as well as maintain the proper relative proportions. Those prominent UTZ areas that are represented in the notional urban area include the dense residential dwellings, apartments/administrative buildings, secondary commercial, widely spaced residential and light industrial areas, and are described in Table 6. It is also important to include an urban canyon feature, which is common to all urban terrain and has characteristics that compromise the performance of military systems.

	Ellefsen UTZ Area	Various Significant Urban Characteristics
SELECTED UTZ AREAS	Dense Residential	Irregular Building Footprints, Building Separation and High Percentage of Building Footprint Coverage
	Widely Space Residential	Courtyard Walls, Gates, Concrete Construction and Parking Lots
	Apartment	Open Courtyards, Parking Lots, Domed-Rooftops and Concrete Construction
	Industrial	Metal Building Construction, Pitched Roofs, Parking Lots, and Loading Ramps
	Secondary Commercial Center	Urban Canyons, Multi-Story Buildings, sidewalks, Curbs, and Street Intersection

Table 6: Urban UTZ Areas

The fifth level of analysis is to determine the building setting morphology. Once the UTZ areas have been identified and sized, the next task is to populate those areas with representative buildings. The UTZ areas were characterized by defining the building densities per square meter, building diversity, the number of stories for each type of building and the placement of building with respect to each other within the UTZ area. In addition to buildings, roads within the environment should be constructed in a representative manner for each of the UTZ areas and this detail is also included in the notional urban area. Each UTZ area will also include significant urban characteristics (e.g., multi-story buildings, urban canyons, water features, roads and streets) that are consistent with the UTZ area.

The five UTZ area types have been reduced in size while maintaining the proportional spatial relationships between them, and incorporated into a notional urban environment. This notional environment is depicted in Figure 14. This minimally defined urban environment is based on the urban area sizing obtained from the Physics, SUT and Operational analysis results. The notional urban area is 200 m X 240 m in dimension, with a minimum number of 57 physical buildings.

Figure 14: Notional Urban Environment

Next Steps

The next steps are to continue through the levels of the Ellefsen and Fordyce, analysis in order to further enhance the urban environment with more detailed urban infrastructure. The Urban Area Data specifies the relationship of the buildings to each other and with other urban infrastructure, such as street setbacks. Building separation must also be incorporated into the area design.

In the sixth level of analysis, the specific building types are identified. It is desirable to identify the most prevalent building types to create the most representative urban area. Understanding the types of building footprints, elevations and floor plans that are likely to be used in the area, will ensure a design of the most representative urban environment.

In the seventh level of analysis, more attributes of the buildings themselves are identified in order to characterize the building types and building construction techniques. Ellefsen and Fordyce conducted research of urban building materials, walls, floor, ceilings and dimensions which can be used when constructing buildings in the physical urban environment.

In the eighth level of analysis, additional infrastructure details of the electromagnetic environments that typify the UTZ areas are further characterized, in order to accurately represent them and provide realism. The urban area will be enhanced with representative electro-magnetic effects that characterize the activity of a live city and provide operational realism. Finally the test capability should also be designed to provide data collection, instrumentation, test planning and control, as well as a distributed connectivity test capability.

Conclusion

A thorough analysis of the characteristics of an urban environment with respect to military systems operating therein was described. The results of this analysis coupled with an understanding of what real urban areas consist of, produced the architecture of a minimum sized notional urban area which spans a 200 m X 240 m dimensional area. This notional urban environment includes 57 buildings representing urban areas of interest.

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